PERSONAL COMMUNICATIONS SERVICES TECHNOLOGY FIELD TRIALS AT THE BOULDER INDUSTRY TEST BED

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Technology field trials for six personal communications services (PCS) common air-interface technologies (whose standards were developed by the Joint Technical Committee on Wireless Access) were performed at the US West Boulder Industry Test Bed (BITB). The BITB provided a common environment for the field testing of all of the technologies. The same configuration (cell site layout, antenna type, and antenna orientation) was used for all of the systems tested as high-tier systems. Similarly, another configuration was used for all systems tested as low-tier systems. Field testing of the technologies typically consisted of four general types: area coverage testing, handoff testing, interference testing, and voice quality testing. Results from these field trials, and descriptions of the measurement and data analysis procedures, are presented in this report.

Key words: adjacent channel interference; area coverage; bit error rate; co-channel interference; expert listener; frame error rate; handoff; Joint Technical Committee on Wireless Access; JTC; mean opinion score; MOS; PCS; personal communications services; received signal strength; Telecommunications Industry Association; TIA; voice quality; word error rate.

1. INTRODUCTION

In the United States, technical standards for the personal communications services (PCS) common air interface were developed in the Joint Technical Committee on Wireless Access (JTC). The JTC was a joint activity between committee T1 of the American National Standards Institute (ANSI) and the Telecommunications Industry Association (TIA). Within the JTC, draft standards for six air-interface technologies for licensed PCS were developed and forwarded to the ANSI. The six technologies are listed below:

1) IS-95-based code-division multiple access (CDMA)
2) IS-136-based time-division multiple access (TDMA)
3) personal access communication system (PACS)
4) PCS 1900
5) Wideband CDMA
6) Omnipoint TDMA/CDMA

Some of the specifications for these technologies are given in Table 1.1. Note that each technology is identified by the specific JTC Technology Ad Hoc Group (TAG) responsible for that technology.

Technology field trials for the six air-interface technologies were performed at the US West Boulder Industry Test Bed (BITB) in cooperation with the JTC. The purpose of the field trials was to (1) demonstrate the performance of the air interface for each technology and (2) to fulfill the JTC requirement that each technology undergo a technology field trial before being forwarded for ballot as a standard.

An individual JTC report was written for each of the six technology field trials. The reports describe the system and test configurations, the types of tests performed, and the results of the analyses of the measured data taken during the field trials. The intent of this report is to provide a consolidation of the six JTC reports. It is intended to be an easily accessible reference that describes the six technology field trials. In both the original JTC reports and in this report, no comparison of the different technologies and no comparison of the performance of the different technologies during the field trials is made.

The original JTC reports present both statistical analyses of the data and maps showing the data as a function of geographical location. In this report, to provide a more concise document, only the statistical analyses of the data are presented. More detailed information about each one of the field trials is available in the individual test reports submitted to the JTC for each air-interface technology [1, 2, and 4-7].

Table 1.1. PCS Technologies Tested During the JTC Field Trials*

	TAG Number					
	TAG 5	**TAG 2**	**TAG 4**	**TAG 7**	**TAG 3**	**TAG 1**
Base Technology	GSM/ PCS1900	IS-95	IS-136	W-CDMA (new)	PACS (new)	Omnipoint (new)
Dates of Field Trial	10/17 - 11/23/94	5/1 - 5/30/95	7/14 - 8/17/95	8/23 - 9/15/95	10/1 - 10/31/95	11/1 - 12/1/95
Access Method	TDMA	CDMA	TDMA	CDMA	TDMA	TDMA/ CDMA
RF Band-width	200 kHz	1.25 MHz	30 kHz	5 MHz	300 kHz	5 MHz
Bit Rate (no overhead)	13 kbps	Two rates available: 8 kbps or 13.3 kbps	7 kbps	32 kbps	32 kbps	32 kbps
System Type	High Tier	High Tier	High Tier	High and Low Tier	Low Tier	High and Low Tier
Error Control (voice)	FEC	FEC	FEC	FEC	None	None
System Capacity Relative to AMPS	2-3x	10x	3x	16x	0.8x	16x

* Courtesy of C.I. Cook, U S West Technologies, Inc. and J. Losh, Motorola, Inc.

The JTC technology field trials took place in a sequential, but not continuously ongoing, fashion over the course of about 14 months. The dates when each trial took place are listed in Table 1.1. The same configuration (cell site layout, antenna type, and antenna orientation) was used for all of the systems tested as high-tier systems. Similarly, another configuration was used for all systems tested as low-tier systems.[1] These configurations were fixed throughout the duration of the field trials and did not vary from one technology to another. This provided a common environment for testing. It did not, however, provide an opportunity for optimizing the performance of each technology. This should be kept in mind when examining the results of the trials.

Field testing for all six of the air-interface technologies typically consisted of four general types: area coverage testing, handoff testing, interference testing, and voice quality testing. The area coverage testing, performed for all of the technologies, included fundamental measurements of received signal strength (RSS) and error rate as a function of location. Handoff testing was performed for all of the technologies except the TAG 7 Wideband CDMA technology. Handoff testing for the TAG 2 CDMA technology included a determination of the percentage of time that the network was in a particular handoff state and the handoff state as a function of location. The types of parameters measured during handoff testing for the other technologies included the change in RSS before and after handoff, the change in error rates before and after handoff, the time between successive handoffs, and the cell site sector in use as a function of location.

Separate measurements for interference testing were also performed for all of the technologies except the TAG 2 CDMA and the TAG 7 Wideband CDMA technologies. No interference measurements were made during TAG 7 testing. All of the TAG 2 measurements were obtained in the presence of simulated interference; no separate interference testing was performed. For the rest of the technologies, both co-channel and adjacent channel interference measurements were made. The goal of the interference measurements was to determine the error rate performance as a function of co-channel and adjacent channel carrier to interference ratios.

Voice quality measurements were made for every technology. For the JTC PCS technology field trials in general, two types of voice quality measurements were made: quasi-stationary measurements and handoff measurements. The quasi-stationary measurements were made at fixed locations on a grid within each cell site. At each fixed location, voice recordings were made as the mobile unit traveled a specified distance. In addition to the voice recordings, various objective measures were recorded such as RSS and bit error rate (BER).

For the voice quality handoff measurements, continuous voice recordings were made as the mobile unit traveled along routes through handoff areas. As in the quasi-stationary measurements, in addition to the voice recordings, various objective measures were recorded, such as RSS and BER. Note that voice quality handoff measurements were not made for the PCS 1900 (TAG 5) and the Wideband CDMA (TAG 7) technology field trials.

While, in general, the same fundamental types of measurements were made for each technology, some differences in the types of measurements are evident, due to the difference in each technology. Also, because each technology was different and the mechanisms for reporting data were different,

[1] High-tier systems are characterized by large cell sizes, high-power handsets, and users traveling at high speeds (in vehicles). Low-tier systems are characterized by small cell sizes, low-power handsets, and stationary users or users traveling at slow speeds (pedestrians).

the reported data is sometimes given in different formats. As an example, one technology may report error rate performance in terms of BER while another technology may report the error rate performance in terms of frame error rate (FER). Differences also existed in what types of data were available at the uplink and downlink for the different technologies. For some technologies, the data for the objective measures (such as RSS and BER) were collected simultaneously at the uplink and downlink. For other technologies, this was not possible. Also, for some technologies, data for the objective measures were collected at the same time as the voice recordings for voice quality analysis. For other technologies, this was not possible. Additionally, as could be expected, since the trials took place sequentially for each technology, the experience gained from conducting one set of trials benefited the trials for the following technologies to be tested. Because of this, test procedures tended to become more refined after the first technology was tested.

Section 2 of this report describes the cell site configurations used during the JTC PCS technology field trials. Sections 3-8 then present the descriptions and results of the measurements and data analyses for each of the technologies tested during the field trials. At the end of each of the these sections, statements from the manufacturers that participated in the respective field trial are given. These statements are identical to those that were provided in the original JTC reports on the PCS technology field trials [1, 2, and 4-7] except for some minor editorial revisions. The manufacturers' comments represent the opinions of the individual corporations only and in no case imply recommendation or endorsement by the National Telecommunications and Information Administration (NTIA).

The Institute for Telecommunication Sciences (ITS) served as independent observers in all of the JTC PCS technology field trials. As independent observers, ITS reviewed test procedures, observed the execution of the tests, and directly participated in the data collection, storage, and analyses.

2. CELL SITE CONFIGURATION

Both high-tier and low-tier systems were tested in the JTC PCS technology field trials. The TAG 3 PACS technology was tested only in a low-tier configuration (in seven different microcells). The TAG 1 Omnipoint technology was tested in both a high-tier and low-tier configuration. Only one of the seven microcells used in testing the TAG 3 PACS technology was used in testing the TAG 1 Omnipoint technology in the low-tier configuration. The same antennas were used for all of the microcells in the low-tier configuration for both the TAG 1 and TAG 3 technologies. The remaining technologies were all tested as high-tier systems. The high-tier systems used the same cell sites and cell site antennas.

Three cells were used in the JTC PCS field trials for high-tier systems: the Walnut Street Central Office (WCO), the Green Mountain Mesa (GMM) site, and the Table Mesa Central Office (TMCO). All cells were located in Boulder, Colorado. The WCO is located in the bottom of a broad valley formed by Boulder Creek. The valley is oriented west to east with ridges rising up to the north and south. The Rocky Mountains rise rapidly, approximately one-half mile to the west. The elevation at 5,370 ft is lower than both the GMM site and the TMCO site. The antennas are located on top of the WCO building. The cell site is in an urban mid- to low-rise environment.

The TMCO is located on a plateau having a slight uphill slope to the south. This cell is located in a suburban residential environment. The Rocky Mountains rise dramatically 2 mi to the west. To the north lies an east-west directed valley. The north side of this valley rises up again after about 2 mi. This creates a coverage shadow down in the valley, but enhanced illumination on the north side.

The GMM site is located on a hilltop 400 ft above the Boulder Valley floor within a large open area in a suburban residential section of Boulder. This site is used both as a serving site to fill in coverage holes in the other sites and as an interfering site. A map of the Boulder area, including the high-tier cell site locations, is shown in Figure 2.1. The distance between the WCO and GMM, GMM and TMCO, and WCO and TMCO sites is 1.8 mi, 1.8 mi, and 3.2 mi, respectively. All high-tier cell sites were sectorized into three sectors: the line bisecting the north sector points true north, the line bisecting the southeast sector points 120° clockwise from true north, and the line bisecting the southwest sector points 240° clockwise from true north. Only the north and southeast facing sectors were used for the GMM site. In TAG 7 testing, the GMM site was not used at all. All three sectors were used for the WCO and TMCO sites except that in TAG 2 testing the TMCO site only used the north-facing sector.

A detailed description of the high-tier cell sites is given in Table 2.1. All high-tier cell sites used two receive antennas and one transmit antenna per sector except in TAG 7 and TAG 1 testing. In TAG 7 testing, one receive and one transmit antenna per sector were used. In TAG 1 testing, four antennas used both to transmit and receive were employed per sector for each cell. Therefore, all high-tier base stations used receive diversity except for TAG 7. TAG 1 used transmit diversity in addition to receive diversity.

For testing of the low-tier TAG 3 PACS technology used in the JTC PCS technology field trials, four microcell sites were used in the downtown Boulder area and three microcell sites were used in south Boulder. The three sites in south Boulder were used for high-speed

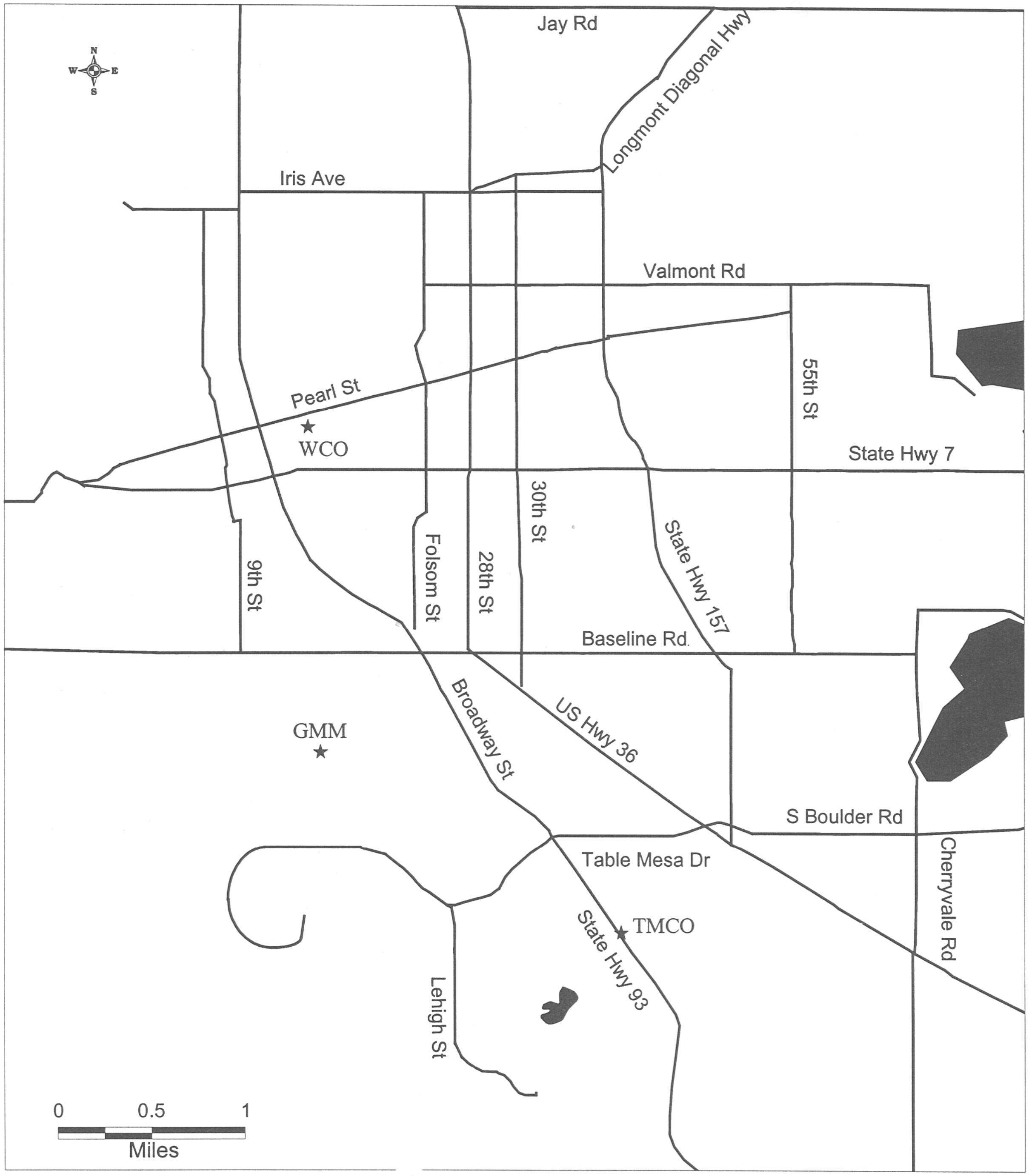


Figure 2.1. High-tier cell site locations in the Boulder, Colorado, area.

Table 2.1. High-Tier Cell Site Configuration Information

Cell Site Description	Location		
	Table Mesa CO	Walnut CO	Green Mountain Mesa[††]
Type of Coverage	Suburban	Light Urban	Suburban/Rural
Latitude	39°58'41.1"N	40°1'4.5"N	39° 59' 32.4"N
Longitude	105°14'31.8"W	105°16'27.6"W	105°16'22.94"W
Height Above Valley Floor	29'	73'	400'
Ground Elevation at Site	5410'	5370'	5800'
Number of Sectors Used	3[*]	3	2
Number of Receive Antennas Per Sector	2[**,†]	2[**,†]	2[**,†]
Number of Transmit Antennas Per Sector	1[†]	1[†]	1[†]
Orientation of Sectors	N,SW,SE[*]	N,SW,SE	N,SE
Antenna Azimuth Beamwidth	120°	105°	120°
Antenna Elevation Beamwidth	7°	7°	12°
Antenna Gain (dBi)	15.6	16.6	13.5
Antenna Null Filling	No	No	Yes
Estimated Cable Loss (dB)	2.0	3.2	3.2

[*] Only the north-facing sector was used in TAG 2 testing and in TAG 1 high-tier testing.

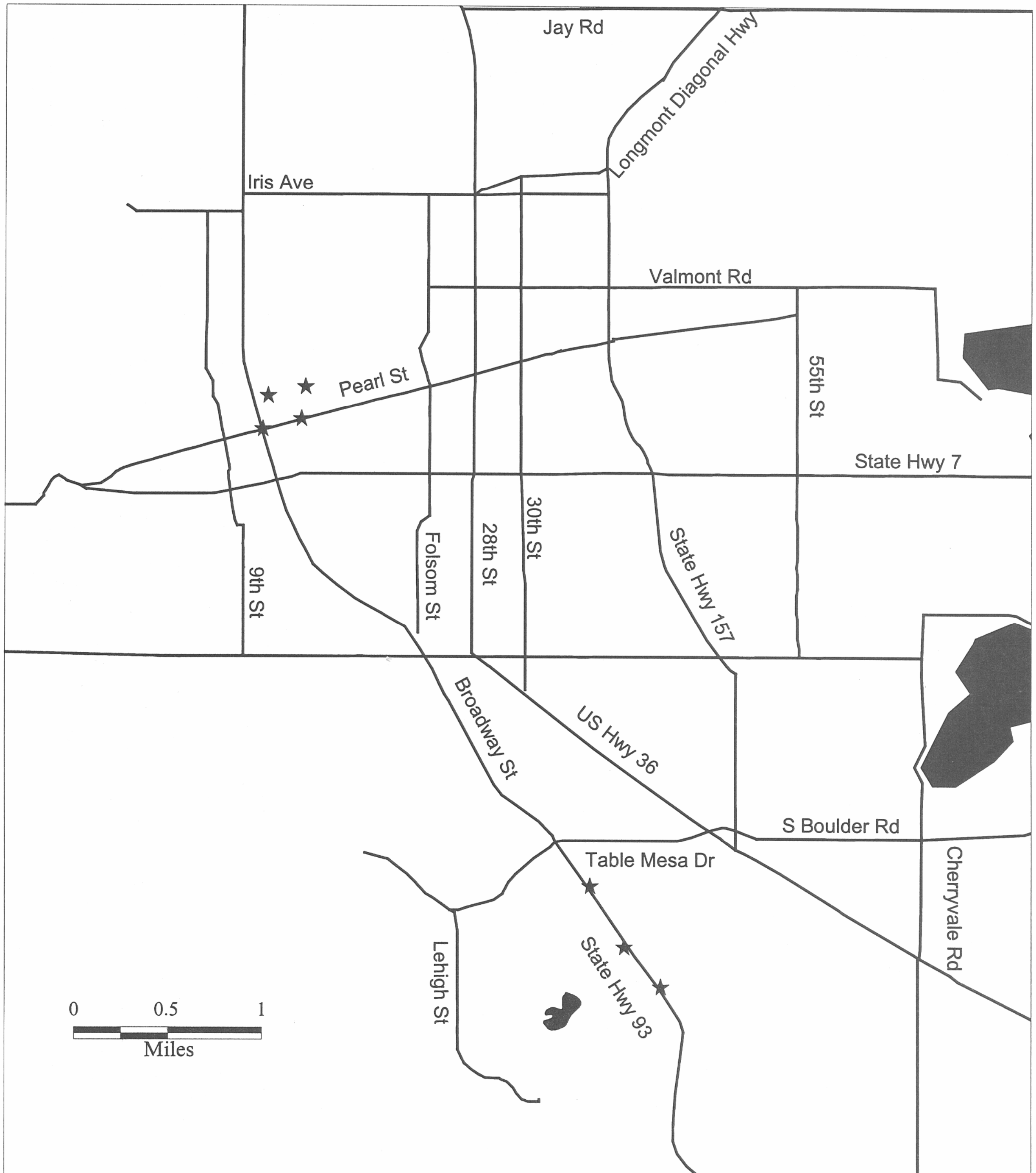
[**] One receive antenna was used per sector in TAG 7 testing.

[†] Four antennas used for both transmit and receive were employed per sector in each cell for TAG 1 high-tier testing.

[††]Not used in TAG 7 testing.

handoff testing. The TAG 1 Omnipoint technology only used one of the downtown Boulder microcells for testing in the low-tier configuration (Site 3). A map of the Boulder area including all the low-tier microcell site locations is given in Figure 2.2. These microcell sites are listed below:

Site 1 - Intersection of Pearl Street and Broadway
Site 3 - Intersection of Pearl Street and 15th Street
Site 9 - On 13th Street halfway between Pine Street and Mapleton Avenue
Site 11 - On 16th Street halfway between Pine Street and Mapleton Avenue
Site 17 - Hanover Street and Broadway
Site 18 - Chambers Street and Broadway
Site 19 - TMCO on Grinnell Street and Broadway



Maps made with MapInfo Professional ™

Figure 2.2. Low-tier microcell site locations in the Boulder, Colorado, area.

The downtown sites used 6-dBi omnidirectional (in azimuth) antennas and the high-speed sites used 9-dBi shaped pattern antennas. The antenna height for all of the microcell sites was 24 ft above street level. All low-tier base stations used receive diversity. In addition, TAG 1 low-tier base stations used transmit diversity. In TAG 1 low-tier testing, two antennas used both to transmit and receive were employed at the base station for Site 3 (the only microcell used in TAG 1 low-tier testing).

3. TAG 5 (PCS 1900) TESTING

This section describes the test plan, methodology, and results for the technology field trial conducted by TAG 5. The PCS 1900 technology tested was the US PCS variant of the GSM and DCS 1800 Standards. The TAG 5 equipment was provided by Motorola, Inc. and Northern Telecom, Inc. The TAG 5 field tests examined area coverage, handoff, and voice quality, and the effects of co-channel and adjacent channel interference on system performance.

The information presented in this section is taken from [1]. This reference provides a more complete and detailed presentation of the TAG 5 technology field testing at the BITB.

3.1 TAG 5 Test System Configuration

The block diagram of the test system configuration is shown in Figure 3.1. The test system consisted of the three cell sites in Boulder (WCO, TMCO, and GMM), a mobile-switching

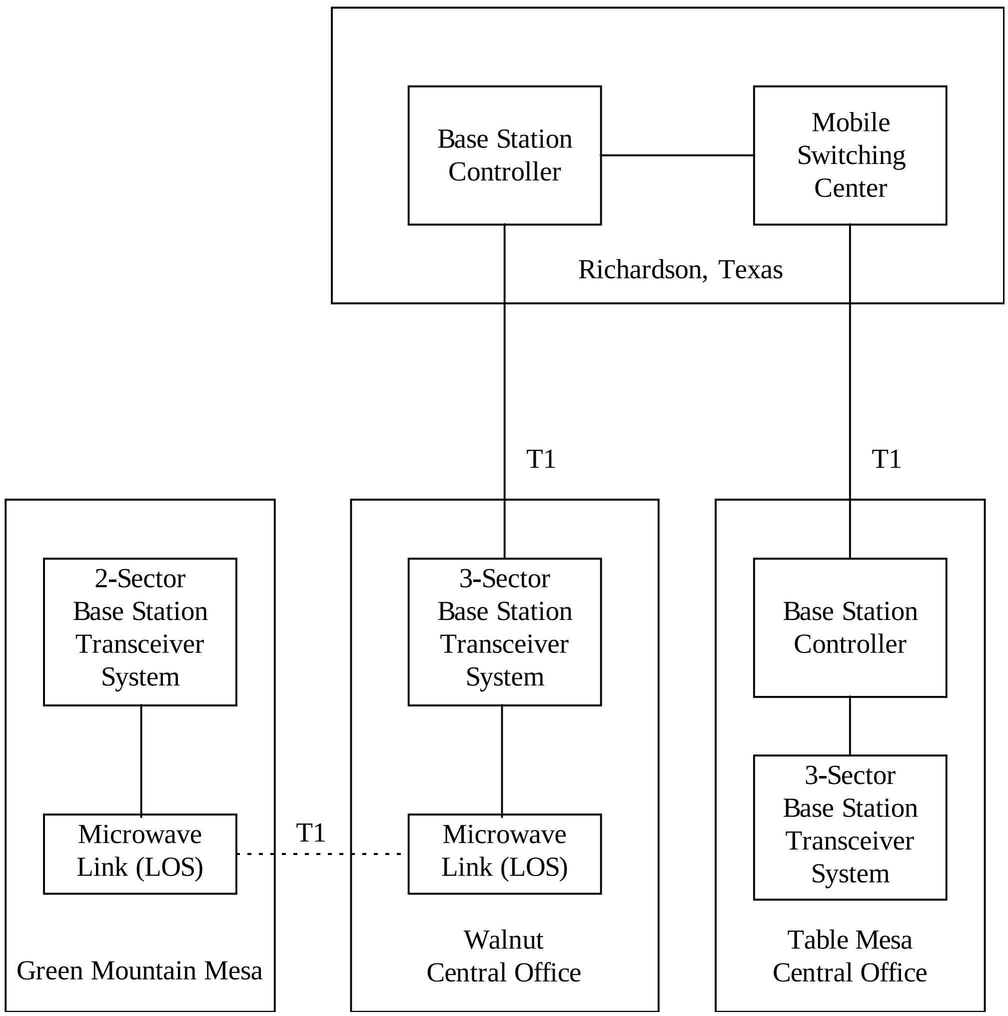


Figure 3.1. Block diagram of the TAG 5 test system configuration.

center (MSC) with a home location register (HLR) in Richardson, Texas, and a base station controller (BSC) in Richardson, Texas. The WCO three-sector base station transceiver system (BTS) was connected to the BSC in Richardson, Texas via a T1 line. A line-of-sight (LOS) microwave link was used to provide a partial T1 link between the GMM two-sector BTS and the WCO BTS. The BSC for the TMCO three-sector BTS was located at the TMCO site; in fact, the TMCO BSC and BTS were housed in the same cabinet. The TMCO BSC was connected to the MSC via a T1 line. The MSC, the BSC in Richardson, Texas, and the BTS's for the WCO and GMM were provided by Northern Telecom, Inc. The TMCO BSC and BTS were provided by Motorola, Inc. The base station receive and transmit frequencies used during the testing for each cell site and sector are given in Table 3.1.

Table 3.1. Base Station Transmit and Receive Frequencies

Cell Site	Sector	Channel #	Receive Frequency (MHz)	Transmit Frequency (MHz)
WCO	North	562	1860.2	1940.2
WCO	Southeast	574	1862.6	1942.6
WCO	Southwest	586	1865.0	1945.0
GMM	North	598	1867.4	1947.4
GMM	Southeast	610	1869.8	1949.8
TMCO	North	622	1872.2	1952.2
TMCO	Southeast	634	1874.6	1954.6
TMCO	Southwest	646	1877.0	1957.0

3.2 Calibration

A major part of the calibration consisted of determining the accuracy of the Rxlev values reported from both the BTS and the mobile unit. Rxlev is a measure of the received signal strength (RSS). Rxlev is related to the RSS by

$$\text{RSS (dBm)} = \text{Rxlev} - 110 \text{ dB.}$$

The accuracy of the Rxlev values reported from both the BTS and the mobile unit were calibrated by connecting the BTS and the mobile unit together via a coaxial cable, high-power and variable attenuators, and two directional couplers. The BTS served as the signal source for testing the accuracy of the Rxlev values reported from the mobile unit. Conversely, the mobile unit served as the signal source for testing the accuracy of the Rxlev values reported from the BTS. The mobile unit (handset) was then placed in a shielded enclosure to prevent coupling from the radiated fields in and around the BTS site.

The first step in the calibration procedure was to determine the losses through the calibration configuration from the transmitter to the receiver. This was accomplished using a signal generator and a spectrum analyzer. Then, a call was established using a fixed attenuation level and the transmitter power was measured. By knowing the losses through the calibration configuration, the RSS was calculated from the measured transmitter power. The calculated RSS was compared to the Rxlev value reported. This procedure was repeated for several different attenuation levels using both the TMCO and WCO BTS's and using two different mobile units manufactured by Motorola, Inc. and two different mobile units manufactured by Northern Telecom, Inc. The maximum difference between the calculated RSS and the corresponding Rxlev value reported was 5.5 dB.

Various transmitter parameters such as transmit power were also characterized as part of the calibration procedure. The results of this characterization are not presented here.

3.3 Area Coverage Testing

The BTS power was set so that the output power for all of the cells was 100-W equivalent radiated power (ERP). Measurements to show area coverage were made with the mobile unit[2] located in a mini-van. The mobile unit was a portable handheld unit that was mounted inside the van on a wooden structure. The structure was located between the two front captain's chairs, 2 ft back from the front window of the van and one foot below the roof. The measurements were taken by driving along routes (radials) away from the site and filling in-between the radials as time permitted. The mobile unit was allowed to handoff within the site to maintain the call as long as possible. Generally, calls were originated close to the cell site and the van was driven away until the lack of radio signal would cause the call to drop. The mobile unit was not able to re-establish the call at that location because the minimum access level was set higher than the sensitivity of the radio. The other sites in the system were turned off for the coverage testing, to determine the area coverage for each cell independently.

3.3.1 TMCO Area Coverage Data

The data were measured and collected at the mobile unit, the GPS receiver, and at the BTS. Data from all three sources were collated with respect to time and combined to provide a file with location, speed, and uplink and downlink Rxlev and Rxqual values in addition to other information about the radio link. Rxqual is a measure of the raw BER. It is related to the raw BER as shown in Table 3.2. All of the data on the uplink were collected (sampled) every 6 s. All of the data on the downlink were collected every 480 ms. In the collated file, the data are listed every second. Of course, data values from the uplink are only available every 6 s so a -1 value was used in the collated file when no data value was available from the uplink. The total number of data points, including both the downlink and uplink, is 6,583.

Downlink Rxlev as a function of distance is shown in Figure 3.2. Note the wide variation in Rxlev values at any given distance. A portion of this variation in the Rxlev data is due to the hilly terrain surrounding this site.

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[2] Measurements were also made with an antenna mounted on the roof outside of the mini-van. For purposes of brevity and because it was not a formal part of the JTC PCS technology field trials, TAG 5 measurements performed with the antenna located out of the measurement van are not discussed in this report.

Table 3.2. Relationship Between Rxqual and the Raw BER

Rxqual Value	Raw BER (%)
0	<0.2
1	0.2 to 0.4
2	0.4 to 0.8
3	0.8 to 1.6
4	1.6 to 3.2
5	3.2 to 6.4
6	6.4 to 12.8
7	>12.8

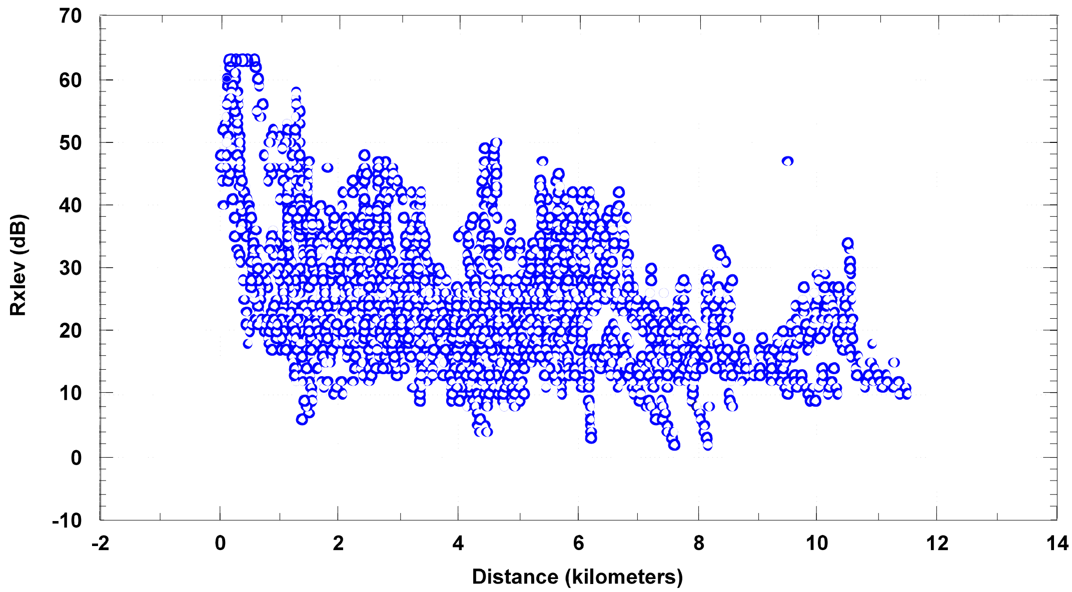


Figure 3.2. Downlink Rxlev vs. distance (TAG 5, TMCO cell).

A rough estimate of the coverage area was determined by assuming that an RSS of -100 dBm or greater is desired. The measured RSS data along all of the routes driven within the cell were used to determine the coverage area. The point along each route where the RSS first dropped below -100 dBm was used to define the coverage boundaries. By doing this, a coverage area of approximately 75 km^2 was obtained.

Figure 3.3 shows the probability density function of Rxlev for both the uplink and downlink. Note that the amount of data for the downlink was larger than the uplink because of the faster data collection rate.

Link balance between the uplink and the downlink was analyzed by generating a scatter plot of Rxlev for the uplink vs. the downlink. Linear regression was then performed to determine the best fit for the data. The best fit line through the data was then used to evaluate the link balance here. Figure 3.4 shows the scatter plot and the results of the linear regression for the case when the effects of uplink power control were not included. As can be observed in Figure 3.4, the links were nearly equivalent.

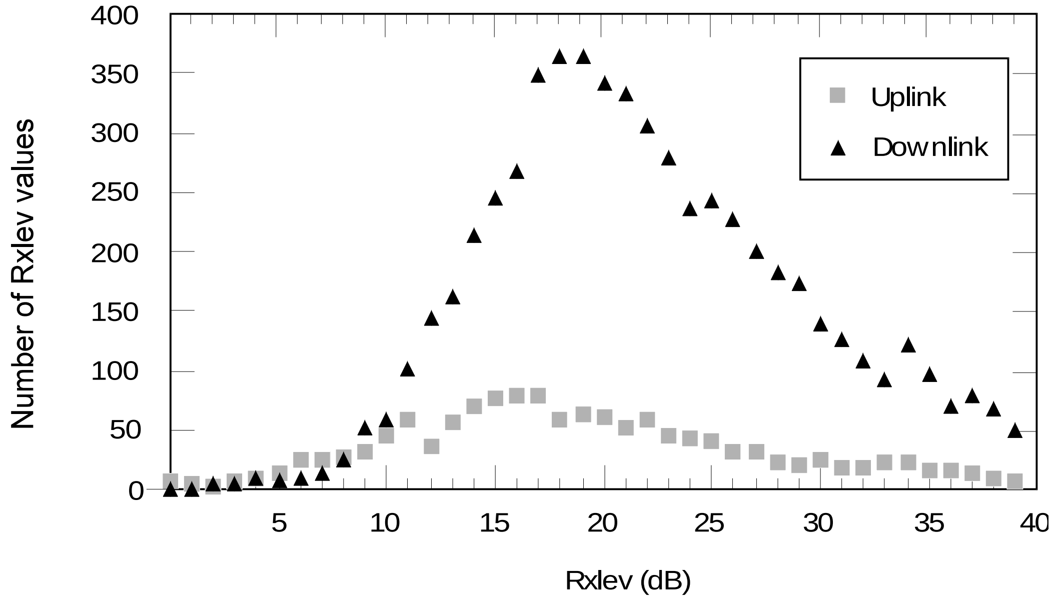


Figure 3.3. Probability density function for Rxlev (TAG 5, TMCO cell).

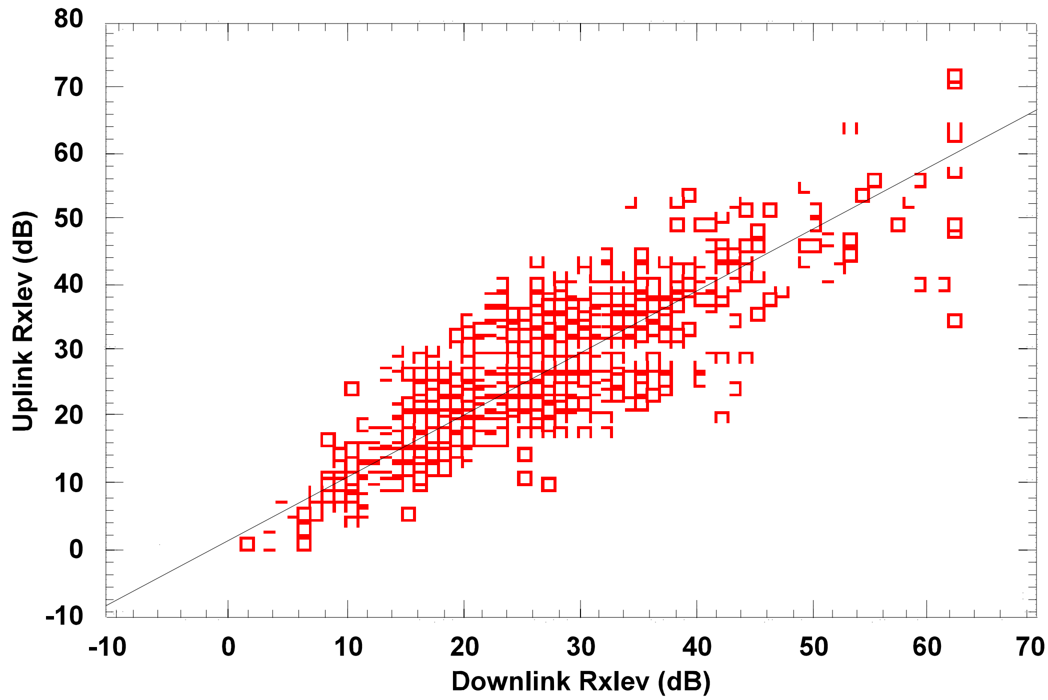


Figure 3.4. Uplink Rxlev vs. downlink Rxlev (TAG 5, TMCO cell).

Figure 3.5 shows a plot of average Rxqual vs. Rxlev for both the uplink and downlink. As expected, the Rxqual values decrease with increasing Rxlev for both the uplink and downlink. Scatter plots of Rxqual vs. Rxlev were generated for both the uplink and downlink as shown in

Figures 3.6 and 3.7, respectively. The results showed that a wide range of Rxlev values (up to 50 dB) gave the same Rxqual value.

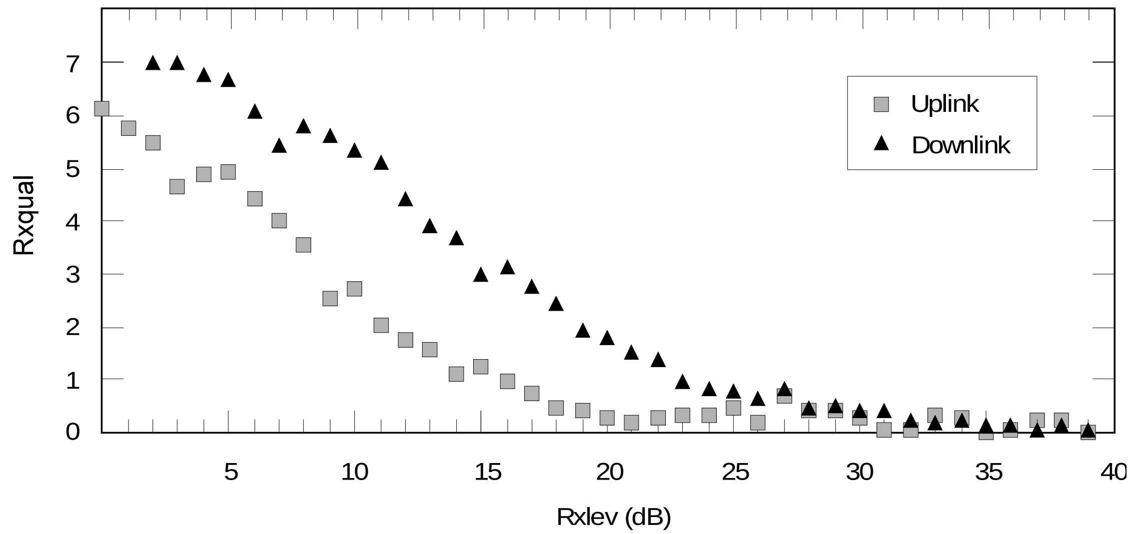


Figure 3.5. Average Rxqual vs. Rxlev for both the uplink and downlink (TAG 5, TMCO cell).

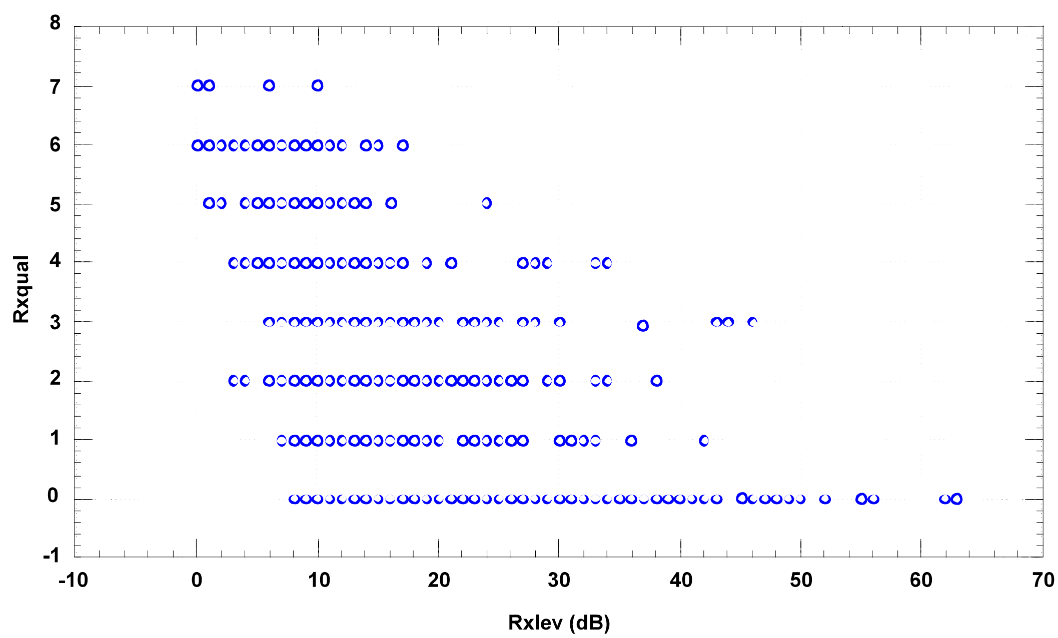


Figure 3.6. Uplink Rxqual vs. Rxlev (TAG 5, TMCO cell).

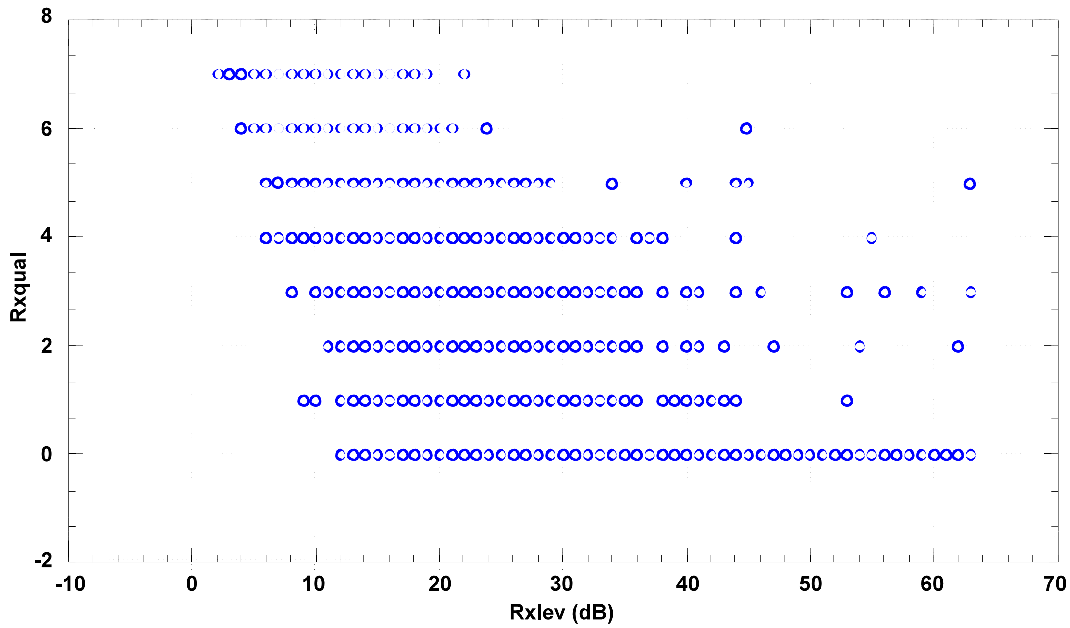


Figure 3.7. Downlink Rxqual vs. Rxlev (TAG 5, TMCO cell).

While no base station (downlink) power control was used, mobile power control was enabled and its effectiveness analyzed. The results showed that the mobile unit was transmitting at its highest power level (30 dBm) 90.4% of the time. Note that this result is dependent on the setting of the power control parameters. When the uplink RSS was greater than about -70 dBm, the mobile unit appeared to reduce its transmitted power level.

3.3.2 WCO Area Coverage Data

The uplink and downlink Rxlev and Rxqual values in addition to other information about the radio link were collected by a protocol analyzer from the T1 link between the WCO BTS and the BSC. Location and speed data were collected from the GPS receiver and dead-reckoning system located in the measurement van. The radio data were collected every 480 ms while the GPS data were collected every second. Data from the protocol analyzer and the GPS receiver were collated with respect to time and combined to provide a single data file. In the collated file, the data are listed every 480 ms. The previous GPS value is used for data records that have no new GPS value. The total number of data points, including both the uplink and downlink, is 16,384.

The location of the WCO cell site with a greater number of tall, closely spaced buildings than in the TMCO cell provided greater decorrelation between the two receive antennas than in the TMCO cell. This provided for greater diversity gain in the base station receiver over the 3-dB gain expected in order two diversity when the branches are correlated. It should be noted that the Northern Telecom BTS reports the Rxlev as the total combined power from the diversity branches.

Downlink Rxlev as a function of distance is shown in Figure 3.8. As in the TMCO cell, there is a wide variation in Rxlev values at any given distance. Although the site was fairly high, it had surrounding buildings that limited its coverage area quite severely. Using the same method as described for the TMCO cell, a coverage area of approximately 50 km^2 was obtained.

Figure 3.9 shows the probability density function of Rxlev for both the uplink and downlink. In this case, the probability density function of Rxlev is nearly the same for the uplink and downlink.

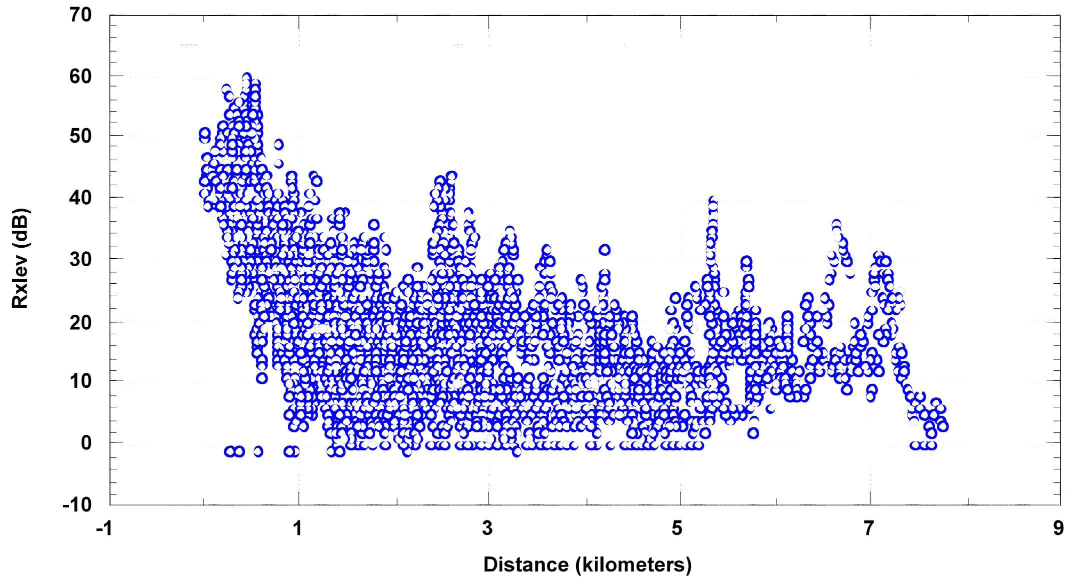


Figure 3.8. Downlink Rxlev vs. distance (TAG 5, WCO cell).

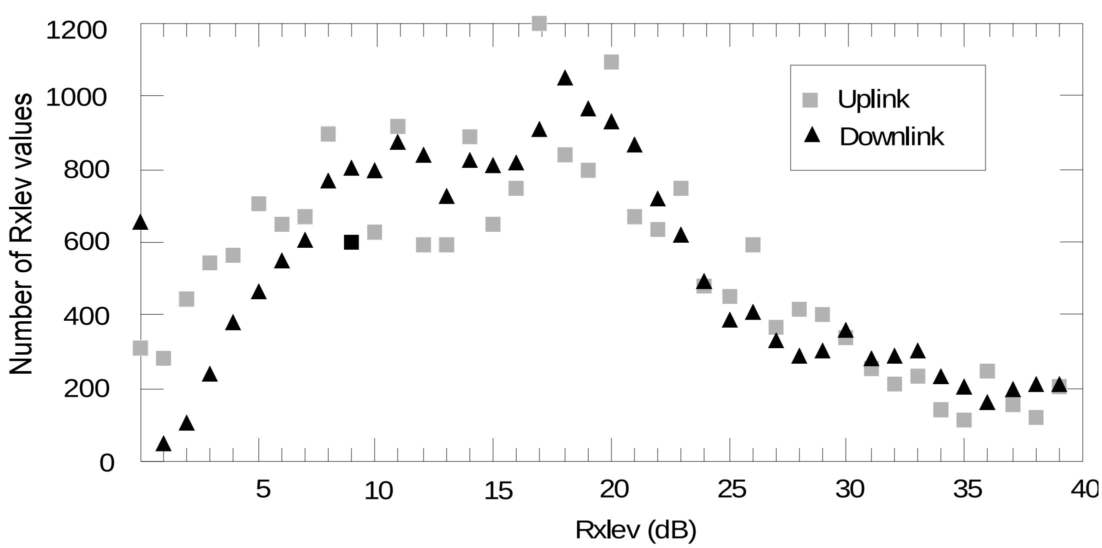


Figure 3.9. Probability density function for Rxlev (TAG 5, WCO cell).

Link balance between the uplink and the downlink was analyzed in the same way as for the TMCO cell by generating a scatter plot of Rxlev for the uplink vs. the downlink. Figure 3.10 shows the scatter plot and the results of the linear regression for the case when the effects of uplink power control were not included. Figure 3.10 shows that the uplink and downlink were roughly equivalent. Figure 3.11 shows a plot of average Rxqual vs. Rxlev for both the uplink and downlink. As in the data for the TMCO site, the Rxqual values decrease with increasing Rxlev for both the uplink and downlink.

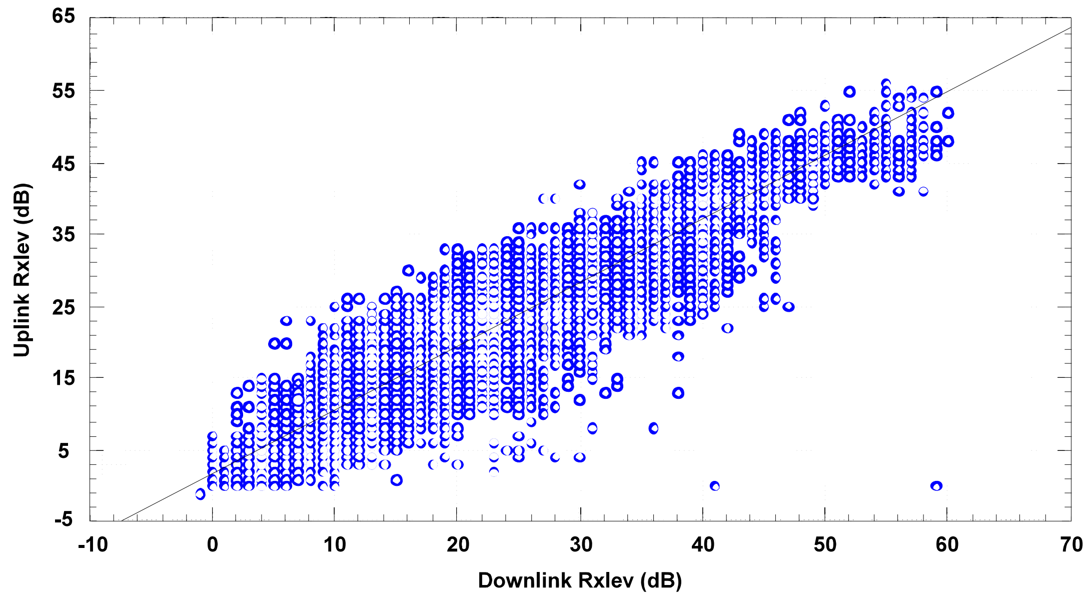


Figure 3.10. Uplink Rxlev vs. downlink Rxlev (TAG 5, WCO cell).

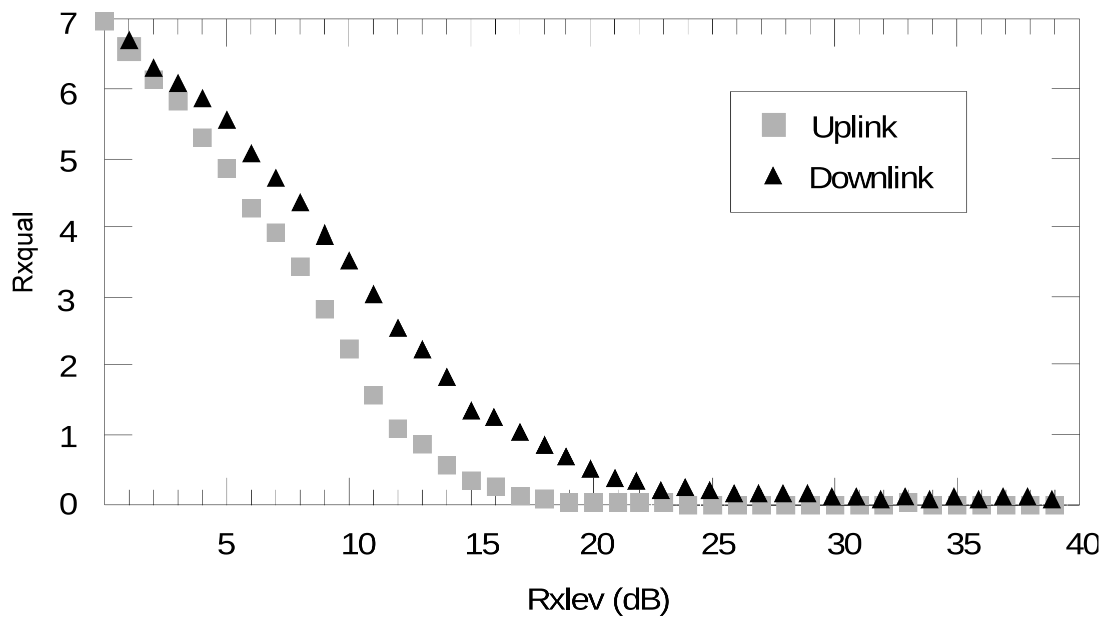


Figure 3.11. Average Rxqual vs. Rxlev for both the uplink and downlink (TAG 5, WCO cell).

Scatter plots of Rxqual vs. Rxlev were generated for both the uplink and downlink as shown in Figures 3.12 and 3.13, respectively. The results showed that a range of Rxlev values gave the same Rxqual value. However, this range of Rxlev values is, in general, smaller for the WCO cell than for the TMCO cell.

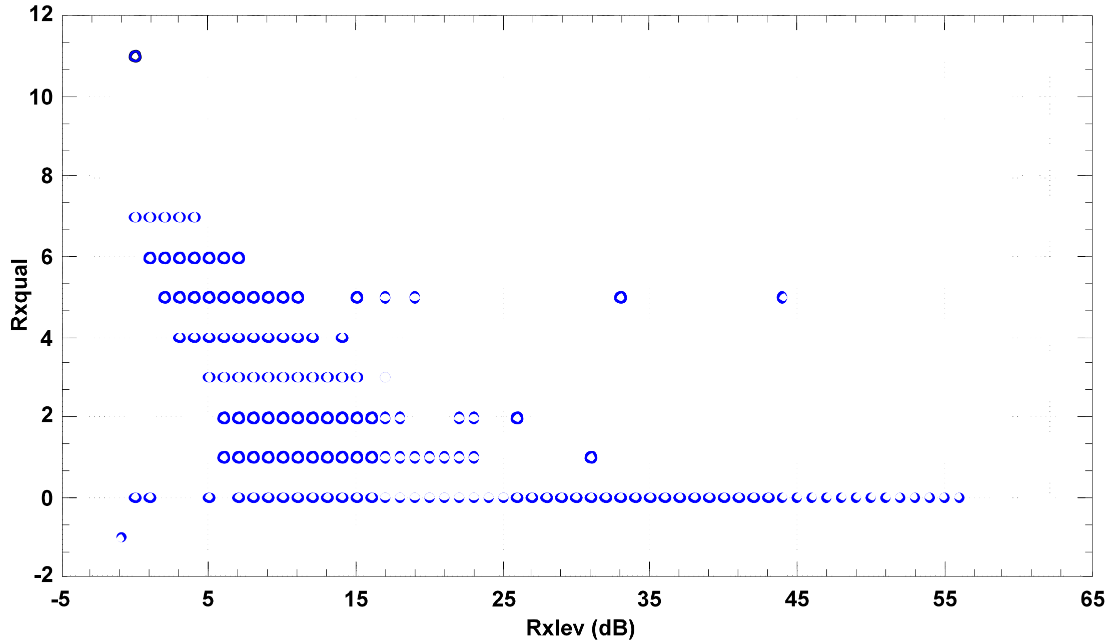


Figure 3.12. Uplink Rxqual vs. Rxlev (TAG 5, WCO cell).

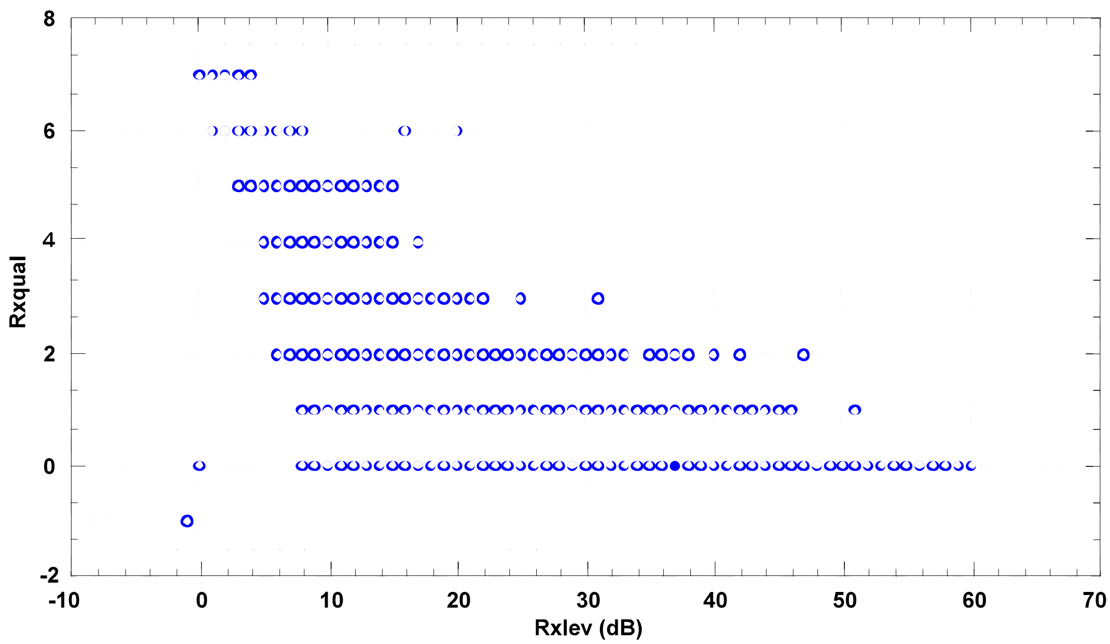


Figure 3.13. Downlink Rxqual vs. Rxlev (TAG 5, WCO cell).

3.3.3 GMM Area Coverage Data

The same data collection methods were used for this site as for the WCO site. However, the total number of data points, including both the downlink and uplink, is approximately 12,000.

Downlink Rxlev as a function of distance is shown in Figure 3.14. As in the TMCO and WCO cells, there was a wide variation in Rxlev values at any given distance. Because this site is located high above the surrounding terrain, line-of-sight propagation extends a long distance away from the BTS. Figure 3.14 shows Rxlev values farther away from the BTS than for either the TMCO or WCO cell sites. Using the same method as described for the TMCO cell, a coverage area of approximately 110 km^2 was obtained. Note that the coverage area is the largest for the GMM site and the smallest for the WCO site.

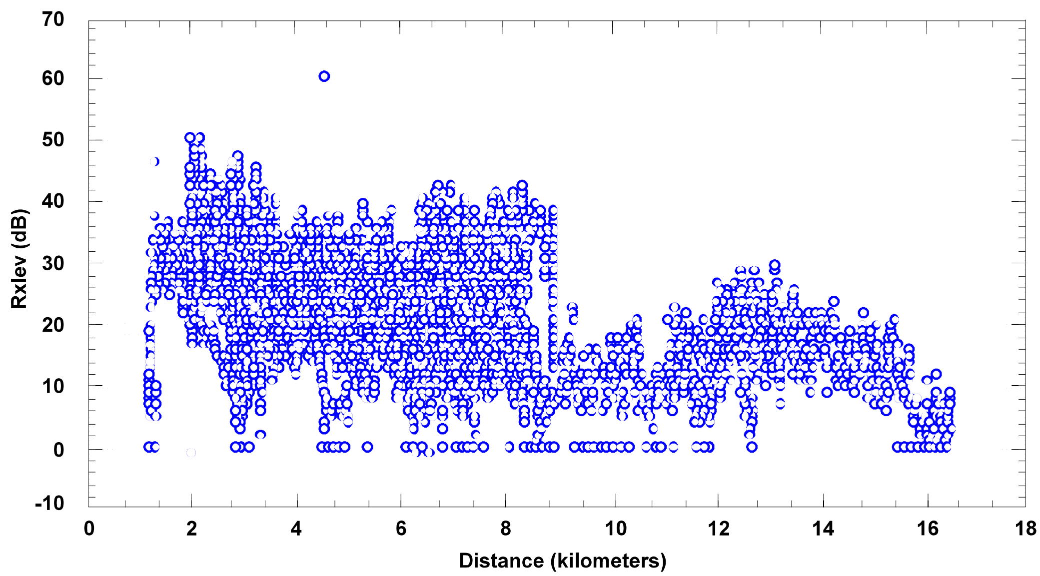


Figure 3.14. Downlink Rxlev vs. distance (TAG 5, GMM cell).

Figure 3.15 shows the probability density function of Rxlev for both the uplink and downlink. For this site, as for the WCO site, the probability density function of Rxlev is nearly the same for the uplink and downlink. Figure 3.16 shows a plot of average Rxqual vs. Rxlev for both the uplink and downlink. As in the data for the TMCO and WCO sites, the Rxqual values decrease with increasing Rxlev for both the uplink and downlink. In this case, the curves for the uplink and downlink are very similar.

3.4 Handoff Testing

Handoff testing was performed by driving the measurement van on routes that would pass through the coverage area of each cell site and each sector within a cell site. Handoff was barred to the GMM site, allowing only handoff between the TMCO and WCO sites.

Handoff testing was performed by establishing an uplink and a downlink simultaneously using two Motorola mobile units that were placed side by side in the handset carrier inside the

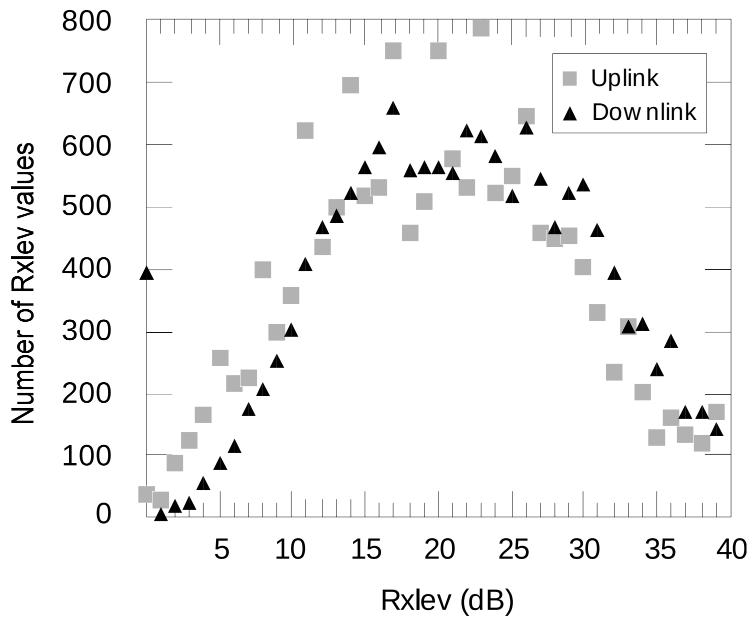


Figure 3.15. Probability density function for Rxlev (TAG 5, GMM cell).

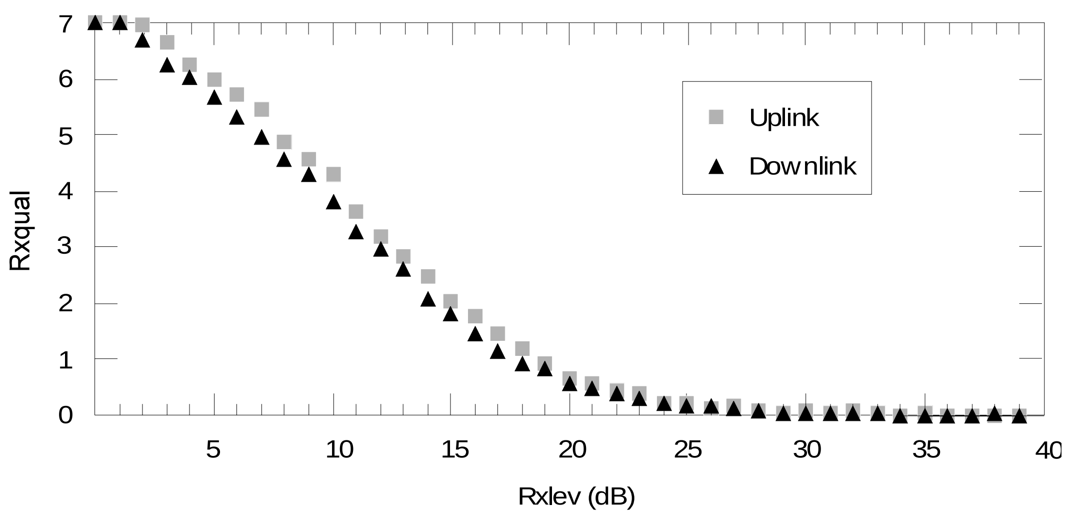


Figure 3.16. Average Rxqual vs. Rxlev for both the uplink and downlink (TAG 5, GMM cell).

measurement van. Data from each link were collected approximately every second. The data recorded included Rxlev, Rxqual, the difference between Rxlev and the access minimum, the handoff type (either between RF channels or between time slots), and the Rxlev of each neighboring cell or sector.

Manufacturers configured their respective sites with generic handoff parameters. As in all of the PCS JTC technology field trials, there was no practical opportunity to optimize any parameters that impacted inter-BSC performance, due to time constraints. Selection of cell site locations was greatly limited to facilities readily available to U S West. As such, the chosen locations were in no way optimal with respect to RF system planning.

The system handoff parameters for both the TMCO and WCO cell sites were set as follows:

Intercell handoff delta = 1 dB
Intracell handoff delta = 4 dB
Intercell access minimum = -105 dBm
Intracell access minimum = -100 dBm

Handoff delta is the difference in RSS levels measured at the mobile unit between the current carrier and a potential carrier for handoff. Access minimum is the minimum RSS that a potential carrier must meet for handoff to be allowed. Note that since the intercell handoff delta was set less than the intracell handoff delta, and the intercell access minimum was set lower than the intracell access minimum, handoff between cell sites was encouraged more than handoff between sectors within a cell. The handoff parameters were chosen to induce handoff between the TMCO and WCO cell sites since there was a lack of sufficient signal overlap between these sites.

Voice quality tapes were played/recorded continuously on the uplink and downlink while the testing was conducted. Each time a handoff occurred, the link, new channel, time, tape counter position, and geographic location were recorded.

Three types of handoff were observed. The first occurred between the sectors at a given cell site. The second occurred between two different cell sites. A third type of handoff was observed, only at the TMCO site, between time slots of a given RF channel.

Data collected from the handoff testing were analyzed to determine the change in the Rxlev and Rxqual values before and after handoff. The time between successive handoffs was also examined. This gives an indication of any “ping-ponging” occurring. Ping-ponging is a rapid sequence of handoffs between cell sites and/or sectors. A total of 63 RF channel-to-RF channel handoffs were examined in the analysis that follows.

The average Rxlev before and after handoff was calculated over six consecutive samples before and after handoff. This corresponds to an average over approximately 3 s. The first sample after handoff was discarded to allow the handset to stabilize. In cases where another handoff occurred before six samples were accumulated, the average was calculated on the number of samples available.

Figure 3.17 presents a histogram of the change in the average Rxlev value (in dB) before and after handoff. Negative values represent cases when the average Rxlev value was actually lower after handoff than before. The cause of this was not definitively determined. Figure 3.18 shows the histograms of change in Rxlev for both intercell and intracell handoffs. Note that the change in Rxlev tends to be greater for the intracell handoffs than for the intercell handoffs directly corresponding to the larger handoff deltas.

Analysis of the handoff data showed that the Rxlev before 22% of the intercell handoffs was fairly low (RSS below -100 dBm), meaning that the area coverage in the cells did not have enough overlap to always complete and ensure a silent transition during intercell handoff. The

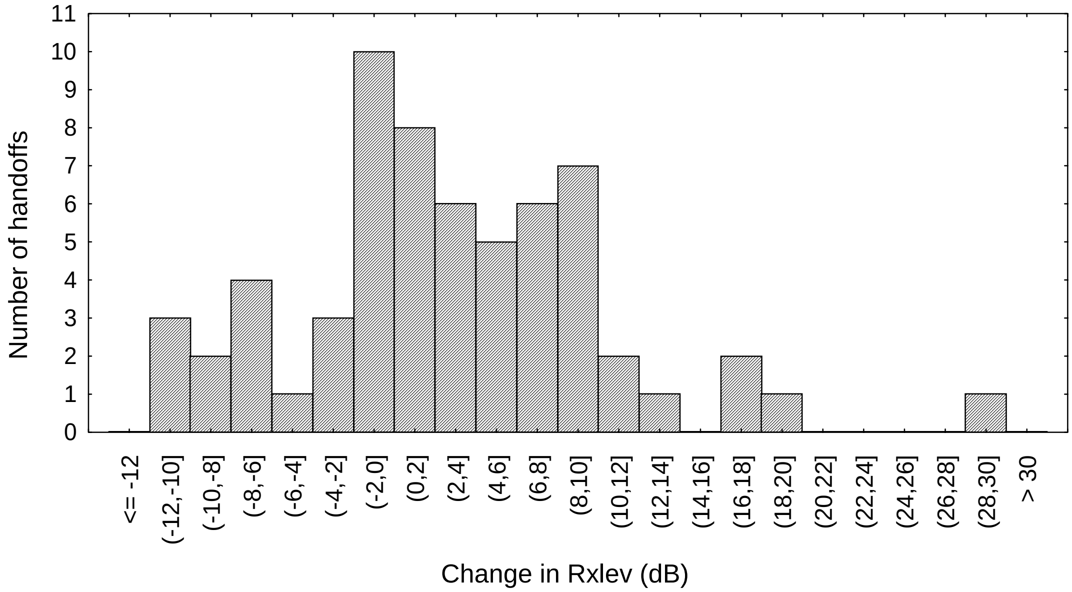


Figure 3.17. Histogram of change in Rxlev during handoff (TAG 5).

change in the average Rxqual before and after handoff was calculated in the same manner as the change in average Rxlev before and after handoff described earlier. Figure 3.19 shows a histogram of the change in the average Rxqual value before and after handoff. Negative values represent cases when the average Rxqual value was higher after handoff than before. Figure 3.20 shows the histograms of change in Rxqual for both intercell and intracell handoffs. Figure 3.21 shows a histogram of the time between successive handoffs. The histogram shows that a relatively large number of successive handoffs had less than 10 s between them. Handoffs occurred with times between successive handoffs up to about 290 s.

3.5 Interference Testing

Interference measurements were performed for the downlink only. These measurements were made as the mobile unit traveled along a square route that included areas with a range of good to poor carrier-to-interference (C/I) ratios. The route was chosen to provide RSS values above the noise floor. Most of the RSS values were above -100 dBm. The route was repeated for each test scenario: no interference, co-channel interference, and adjacent channel interference. Frequency hopping and discontinuous transmission (a transmission mode using a variable speech-coding bit rate) were not employed during these tests.

For the co-channel interference measurement, the WCO north sector was used as the intended source. The GMM north sector was used as the source for the co-channel interference. Both the GMM north sector and the WCO north sector were tuned to the same frequency. A second carrier, at a different frequency, was transmitted from the GMM north sector. This carrier was used to measure the RSS of the interfering signal from the GMM site at the mobile unit. Note that in this configuration, the channel used for monitoring the interference level fades independently of the actual interfering signal.

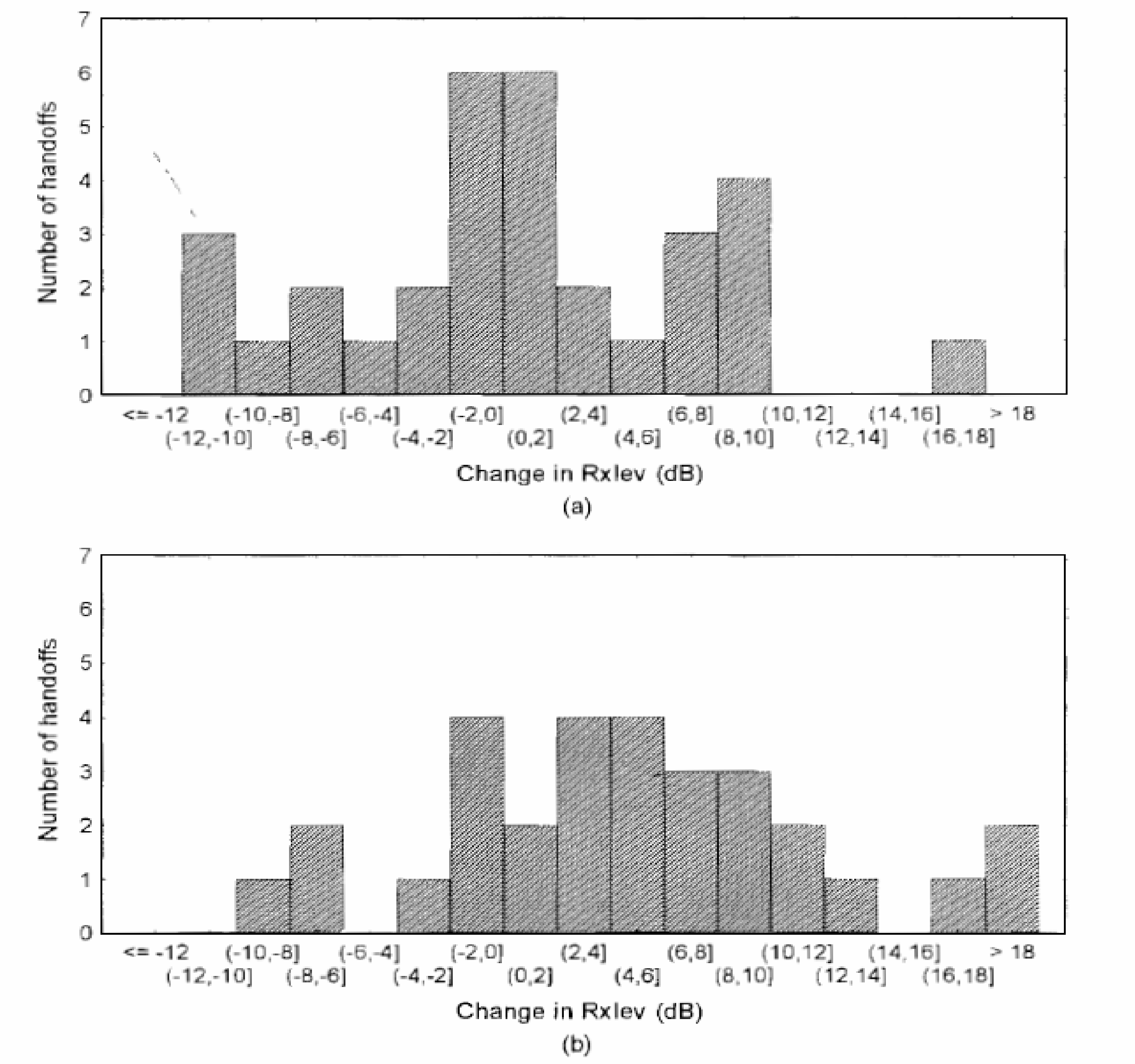


Figure 3.18. Histograms of change in Rxlev for (a) intercell and (b) intracell handoffs (TAG 5).

For the adjacent channel interference measurement, the WCO north sector was again used as the intended source. The GMM north sector was used as the source for the adjacent channel interference. The carrier for the adjacent channel interferer was set to a frequency 200 kHz away from the intended source's carrier.

Figure 3.22 shows average Rxqual as a function of the C/I for both the co-channel and adjacent channel cases. As expected, when the C/I is increased, lower values of Rxqual are seen; i.e., the bit error rate decreases. Also as expected, to achieve the same Rxqual value, a much lower C/I (approximately 20 dB lower) is required for the adjacent channel interference than the co-channel interference.

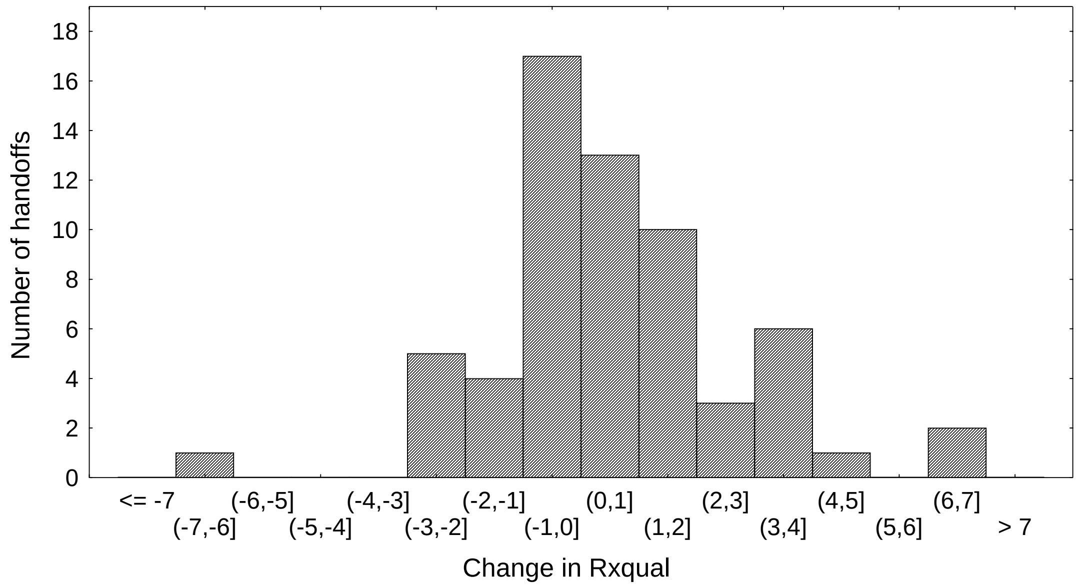


Figure 3.19. Histogram of change in Rxqual during handoff (TAG 5).

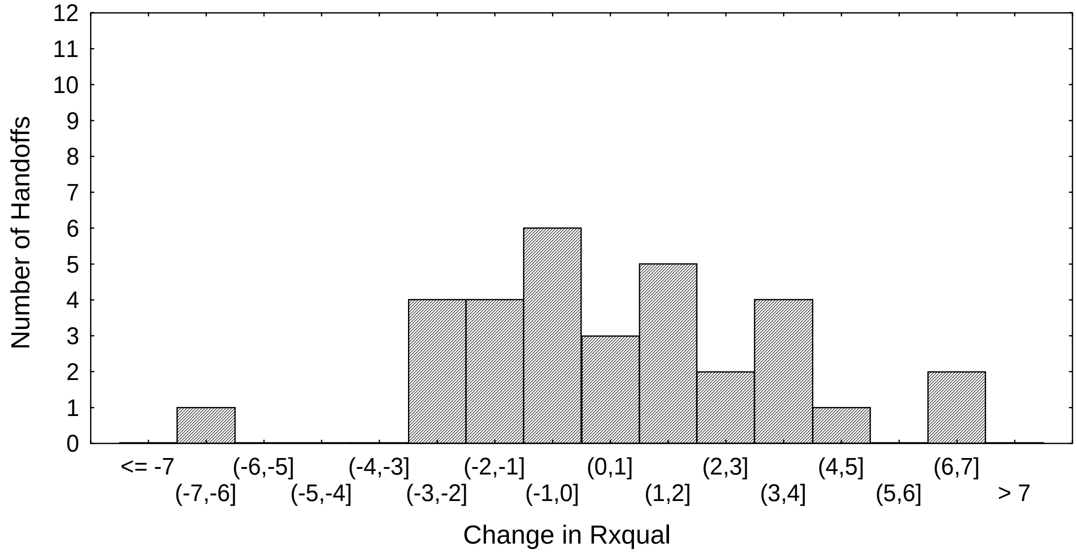
3.6 Voice Quality

For the JTC PCS technology field trials in general, two types of voice quality measurements were made: quasi-stationary measurements and handoff measurements. The quasi-stationary measurements were made at fixed locations on a grid within each cell site. At each fixed location, voice recordings of transmitted voice signals were made as the mobile unit traveled a specified distance. In addition to the voice recordings, various objective measures were recorded, such as RSS and BER.

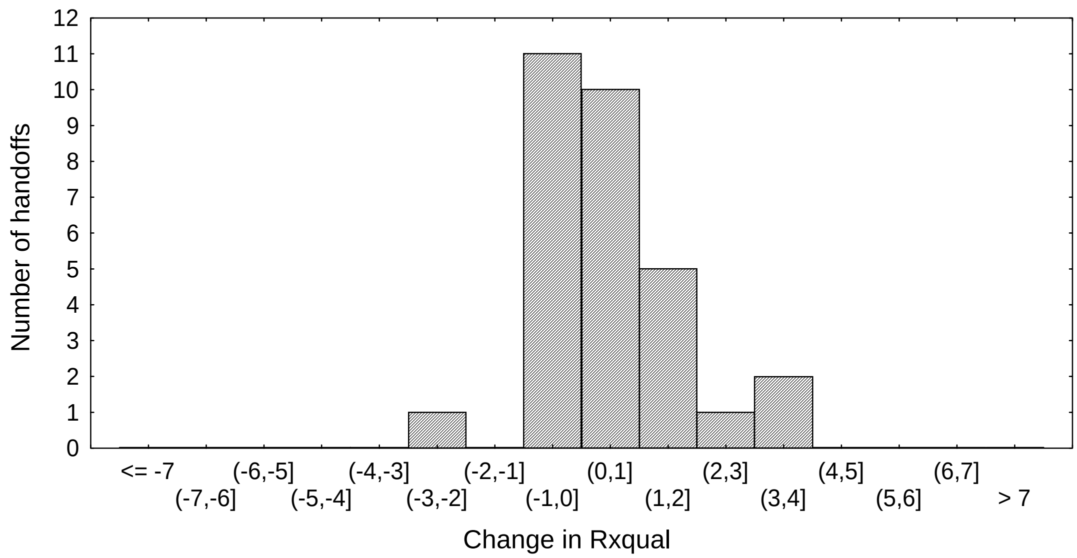
For the voice quality handoff measurements, continuous voice recordings were made as the mobile unit traveled along routes through handoff areas. As in the quasi-stationary measurements, in addition to the voice recordings, various objective measures were recorded such as RSS and BER. Note that voice quality handoff measurements were not made for the PCS 1900 (TAG 5) and the Wideband CDMA (TAG 7) technology field trials.

3.6.1 Quasi-stationary Measurements

Voice recordings and Rxlev and Rxqual data were collected at locations on a 0.5-mi grid that encompassed the expected coverage area for the TMCO and WCO sites. Eighty-two locations were identified as measurement sites for the quasi-stationary measurements: 40 centered around the TMCO site and 42 centered around the WCO site. Measurements were taken at 78 of these locations for the TAG 5 testing. Only one cell was activated at a time. Measurements were taken at the 40 locations around the TMCO cell site when the TMCO cell was active. Similarly, measurements were taken at 38 of the 42 locations around the WCO cell site when the WCO cell was active. At each location, data were collected as the measurement van traveled at one of two speeds. The vehicle traveled either 10 m or 100 m over the sample time. The sample time was the same for both cases. The particular vehicular speed used at each location (distance traveled



(a)



(b)

Figure 3.20. Histograms of change in Rxqual for (a) intercell and (b) intracell handoffs (TAG 5).

over a fixed sample time) used in the TAG 5 testing was predefined and is shown on the map in Figure 3.23.

The quasi-stationary voice quality measurements were made at various subsets of the 82 defined locations for all of the high-tier testing in the JTC PCS technology field trials, except for TAG 7. While the TAG 7 technology was tested in a high-tier configuration, the quasi-stationary voice quality measurements were made at different locations than the other

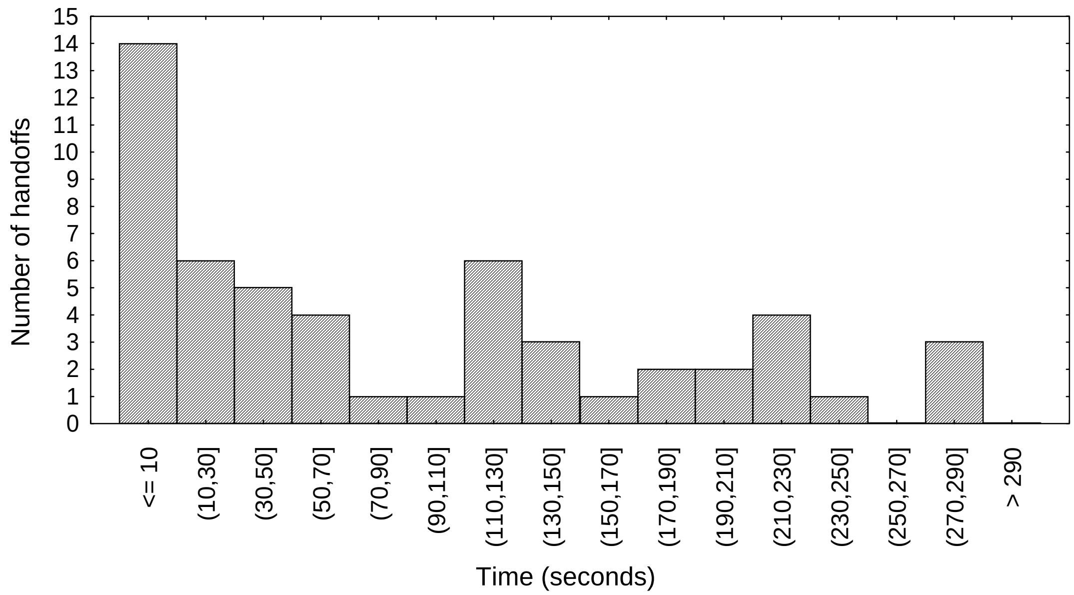


Figure 3.21. Histogram of time between successive handoffs (TAG 5).

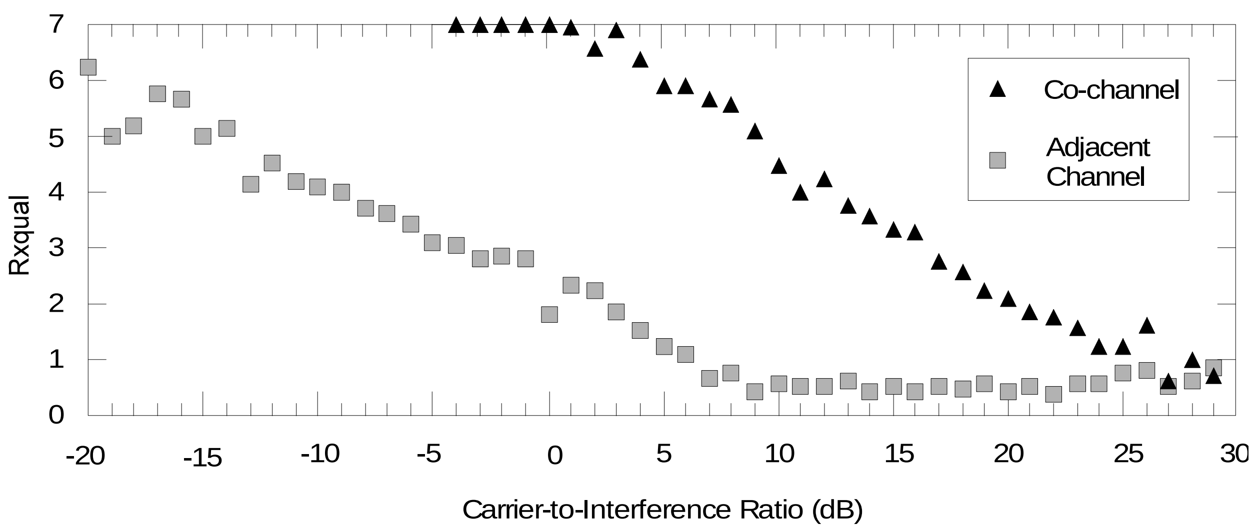


Figure 3.22. Average Rxqual vs. carrier-to-interference ratio (C/I) for co-channel and adjacent channel interference (TAG 5).

technologies that were tested in a high-tier configuration. All of the JTC PCS technologies were tested in a high-tier configuration except for the TAG 3 PACS technology. (The TAG 1 technology was tested in both a high-tier and low-tier configuration.) The TAG 3 PACS technology was tested only in a low-tier configuration.

The measurements were taken at each location by establishing a call between the mobile and landline telephones. While the measurement van was in motion, an audio source tape was transmitted over the uplink and downlink simultaneously. The source tape transmitted over each link was identical and contained 75-80 s of spoken standard Harvard sentences; 10 spoken by a male and 10 spoken by a female. These sentences are phonetically balanced and include all the sounds in the American usage of the English language. The 10 male and 10 female sentences together as a group are referred to as a *voice segment* in the remainder of this report.

The received voice transmissions were recorded on analog audio tape at the receiver for the uplink and at the receiver for the downlink. The recorded voice segments were then digitized with 16-bit resolution at a 22-Ksample/s rate and stored on a hard disk drive. Rxlev and Rxqual data were collected simultaneously with the recorded voice transmissions. During all data processing, the average Rxlev and Rxqual values were computed for each recorded voice segment.

For the quasi-stationary measurements, voice quality of the voice segments was determined by both mean opinion score (MOS) and expert listener techniques. The following sections discuss these techniques and present the results based on the application of these techniques.

3.6.2 Mean Opinion Score Assessment

The MOS technique for determining voice quality entails a group of listeners (called subjects) rating the quality of voice segments subjectively. For each voice segment, the results from all subjects in the group are then averaged to form the MOS.

To accomplish the MOS testing, a pool of 30 subjects was recruited from the Boulder, Colorado area. Each of the following age groups were represented within the subject pool: 18-25, 25-35, and 35-50, and those over 50 years of age. There were an equal number of male and female subjects. The subjects were cordless, noncellular telephone users.

Four groups of subjects from the subject pool were formed: two groups of eight and two groups of seven. The subjects were asked to rate voice segments by answering the following questions after each segment was presented:

1) How would you rate the overall quality of the sound? (on a 5-point scale where 5=excellent, 4=good, 3=fair, 2=poor, and 1=bad);

2) How annoying are any additional sounds you might hear? (not at all annoying, slightly annoying, annoying, very annoying, or extremely annoying); and

3) Would this be acceptable as portable service? (acceptable or unacceptable).

First, the subjects in each of the four groups were presented with two practice voice segments to rate. Then the subjects in each of the four groups were asked to rate one quarter of all the voice segments taken from the measurements. In each voice segment the 10 male sentences were presented before the 10 female sentences half of the time. In addition, the order of presentation of the voice segments was randomized.

For each voice segment, voice quality ratings (answers to the question “How would you rate the overall quality of the sound?”) from each subject within a group were averaged to obtain

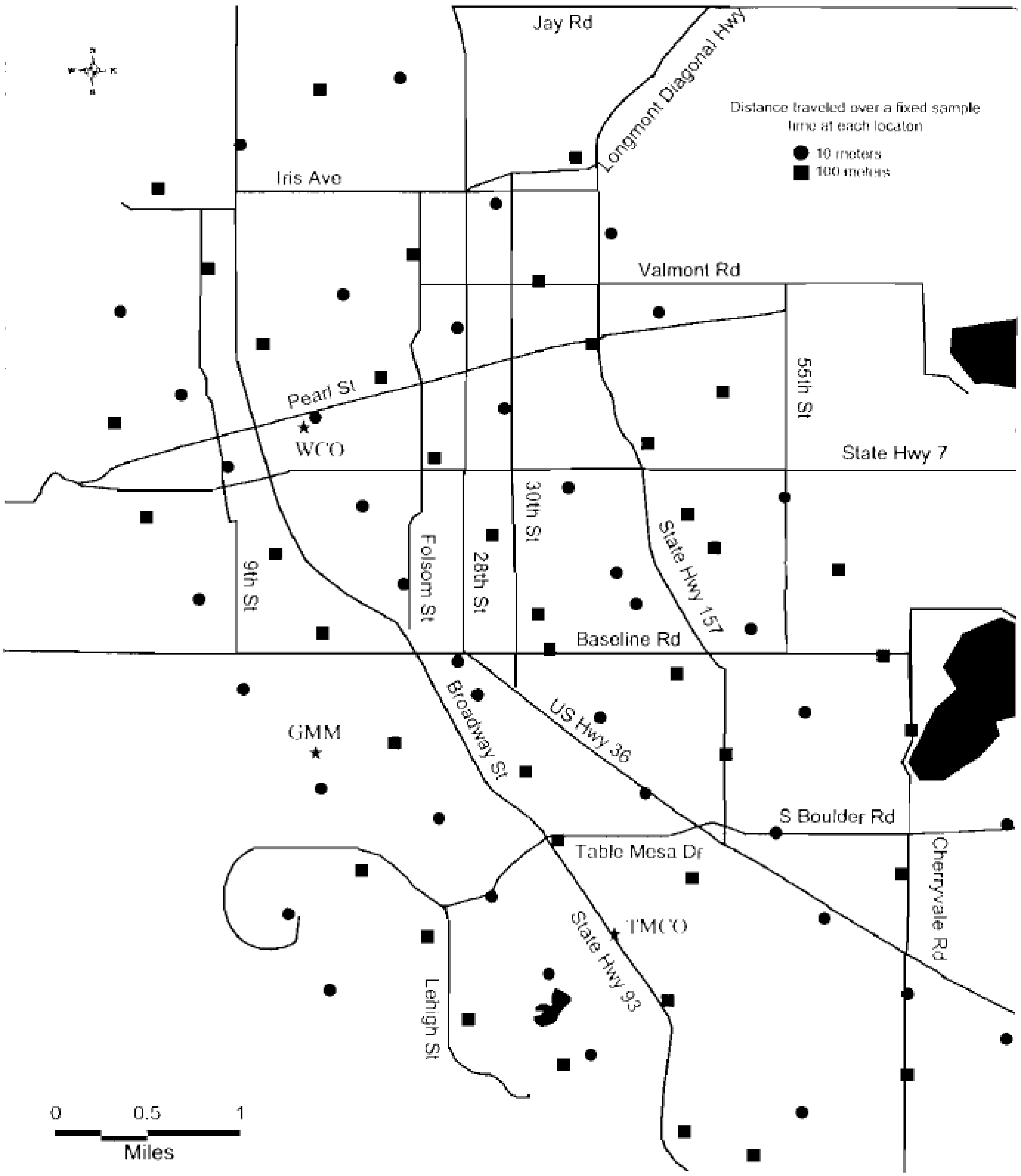


Figure 3.23. Quasi-stationary measurement locations and vehicular speed used at each location for TAG 5.

an MOS. The results from all four of the groups (for both the uplink and downlink for the WCO cell only) are shown in the histogram in Figure 3.24. Overall, the voice segments were marked favorably, with 80% of the segments rated between fair and excellent. The mean MOS was 3.09 and the standard deviation was 0.80.

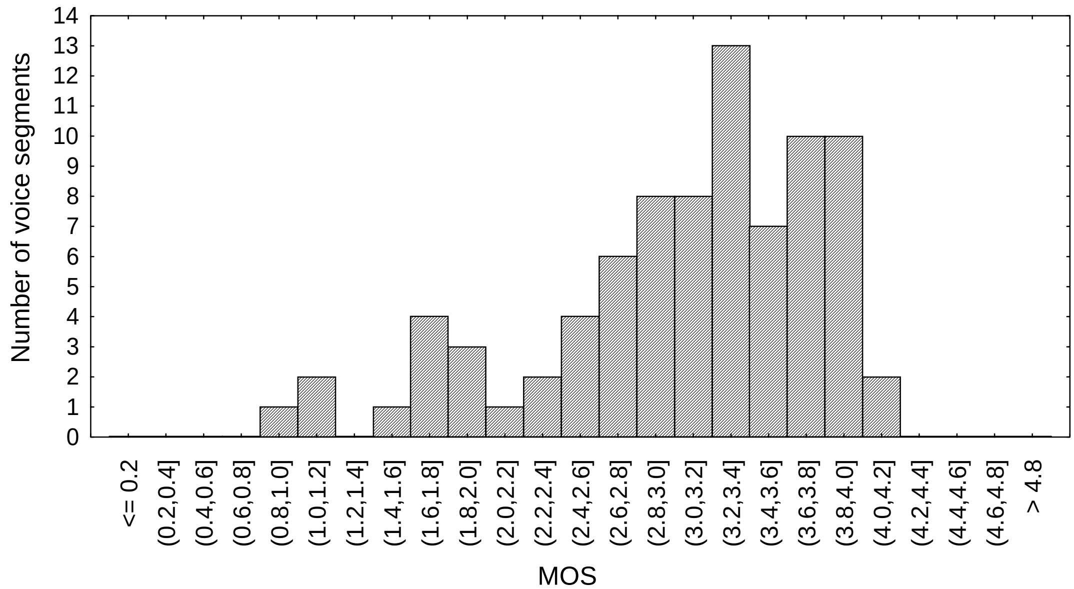


Figure 3.24. Histogram of mean opinion scores (MOS's; TAG 5, WCO cell).

Scatter plots of MOS vs. average Rxlev and MOS vs. average Rxqual, shown in Figures 3.25 and 3.26, respectively, were generated to help determine the relationship between MOS's and the objective measures. These plots show a large variation in MOS's at all values of Rxlev and Rxqual.

Pearson product-moment correlations were performed to determine the correlation between MOS and average Rxlev, between MOS and average Rxqual, and between average Rxlev and average Rxqual. The correlation coefficient between MOS and average Rxlev was 0.22 and that between MOS and average Rxqual was -0.34. The negative correlation coefficient occurs because increasing MOS's correspond to decreasing Rxqual values. The low correlation coefficients imply that a strong linear relationship does not exist between both MOS and average Rxlev and MOS and average Rxqual. The correlation coefficient between average Rxlev and average Rxqual was -0.67. While this shows a stronger correlation than between the MOS's and the objective measures, a strong linear relationship between the two objective measures still does not exist.

While there does not appear to be a strong linear relationship between MOS and the objective measures, there still may be a consistently increasing or decreasing relationship between them.

The Spearman rank correlation can be used to determine if a consistently increasing or decreasing trend may exist between MOS and the objective measures. Spearman rank correlations were performed to determine the correlation between the ranks of MOS and the

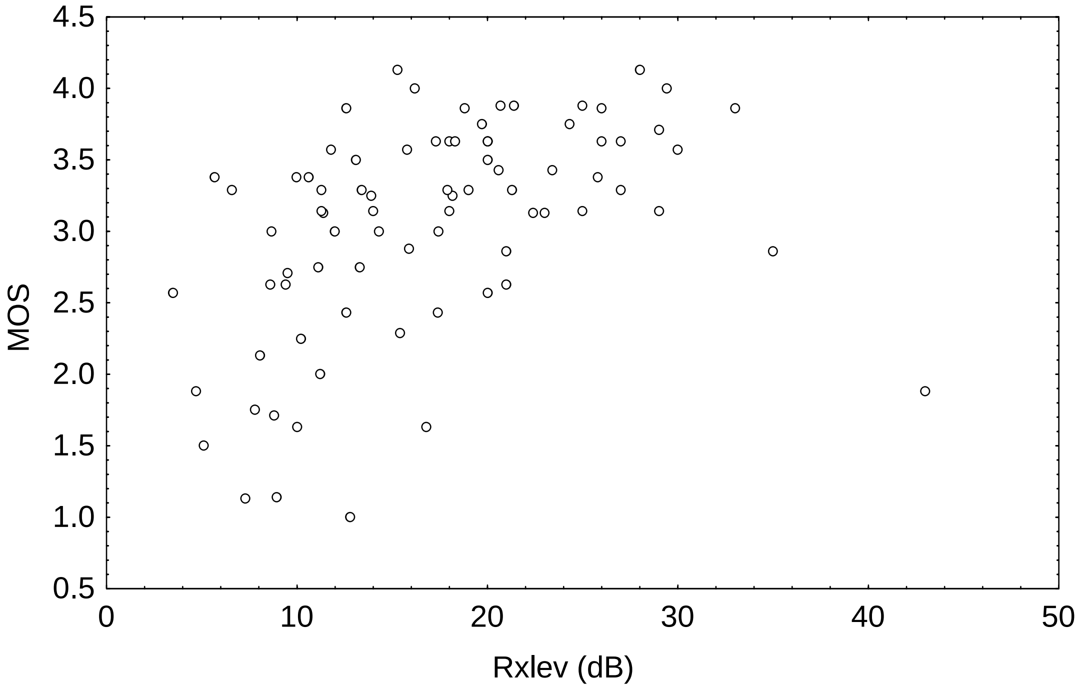


Figure 3.25. Mean opinion score (MOS) vs. Rxlev (TAG 5).

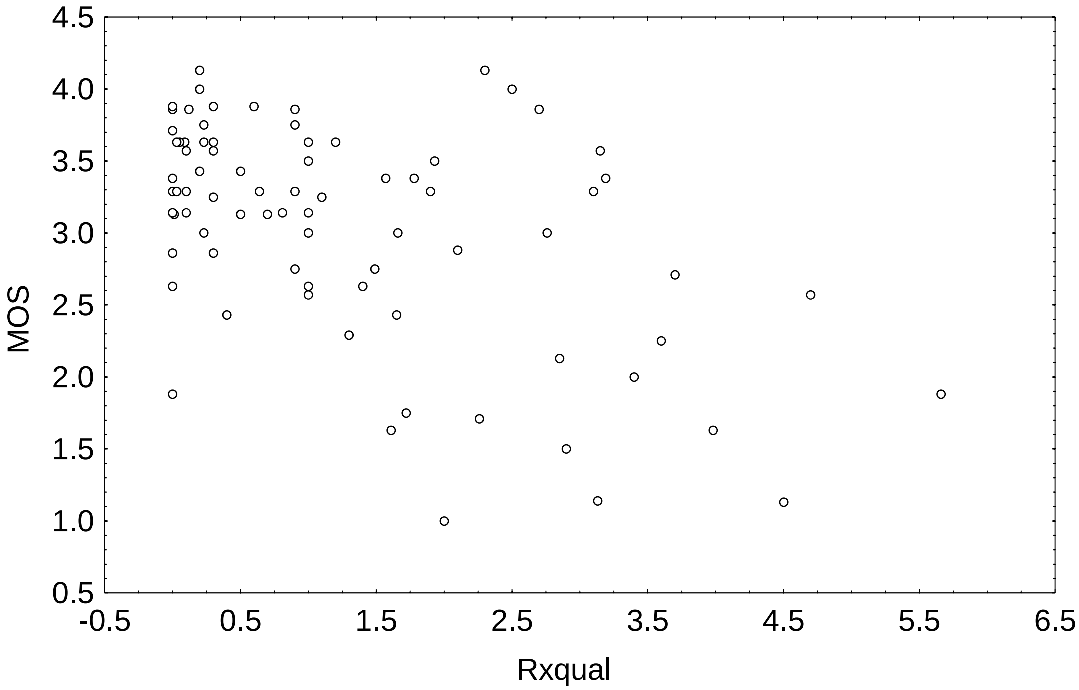


Figure 3.26. Mean opinion score (MOS) vs. Rxqual (TAG 5).

ranks of average Rxlev and between the ranks of MOS and the ranks of average Rxqual. The Spearman rank correlation coefficient between MOS and average Rxlev was 0.28 and that between MOS and average Rxqual was -0.27. These low rank correlations between MOS and averaged objective measures suggest that a consistently increasing or decreasing relationship between MOS and the objective measures does not exist.

Note, the values used for Rxlev and Rxqual above were averages over the entire length of the voice segments. The objective measures, averaged over the entire voice segment, do not appear to be accurate predictors of listener satisfaction. A small number of low instantaneous Rxlev values or high instantaneous Rxqual values can significantly influence the MOS's but not affect the average Rxlev or Rxqual value. By analyzing the instantaneous variation of these objective measures within each voice segment, further insight might be gained on the behavior of the MOS's. By considering minimum Rxlev or maximum Rxqual values, a better understanding of the nature of the MOS's might be obtained.

By gathering listeners' comments from post-test questionnaires, more information about the nature of MOS's was obtained. Namely, it is evident from questionnaires that there are several types of distortions in quality possible in the voice recordings of the PCS 1900 system according to listeners:

1) muting and synthesization of human voice (e.g. "mechanical voice," "blanks"),
2) fading within a voice sample ("voice signals becoming faint"),
3) background noise, especially "echo" (prevalent in most samples), and
4) distortions in higher frequencies ("ringing" or "shrill" sounds during higher frequencies, "inability to hear the letter 's' ").

Most importantly, the nature of the distortions are judged differently by different listeners. In other words, each of the above distortions are weighed on different scales by each listener. Some listeners judged distortions 1 and 2 more harshly than other listeners. Distortions 1 and 2 are most likely related to RSS. Distortions 3 and 4,[3] seemingly not affected by RSS, were also judged more harshly by some listeners than others. This caused voice segments with high Rxlev values to have lower MOS's than expected. Since distortions 1-4 were judged differently by different listeners, the MOS's were affected.

One listener mentioned a concern over his ability to "focus for 2 hours." It is possible that the experimental design was not the most ideal. By being asked to judge the overall quality of a voice segment (over 1 min in duration) a listener tends to average the score to include good parts and bad parts. Their ratings then might be affected more by how the latter part of a segment sounds. They are affected by what is fresh in their minds (recency effect). They may also have been overly influenced by how the beginning of a segment sounded (primacy effect). Because of the length of a given segment, it may have been difficult to concentrate and make an accurate judgment on the entire segment. Alternative experimental design considerations are necessary to ensure that this difficulty in concentrating and making an accurate judgment on the entire segment is not occurring in testing.

[3] Distortions 3 and 4 tended to be more obvious in voice segments where distortions 1 and 2 were not present.

3.6.3 Expert Listener Assessment

In addition to being rated by listener panels in MOS testing, the voice segments were rated by an expert listener. The expert listener was trained to emulate the responses of listener panels to the question “Would you consider this acceptable as portable service?” The expert listener rated voice segments according to a three-point scale of acceptability: definitely acceptable, marginally acceptable, and unacceptable. Listener panel responses to this question were used to categorize a voice segment according to this same three-point scale of acceptability. Voice segments were categorized from the listener panel responses as definitely acceptable if more than 70% of the subjects rated the segment as acceptable, marginally acceptable if 30-70% of the subjects rated the segment as acceptable, and unacceptable if less than 30% of the subjects rated the segment as acceptable.

A training software package was developed that outlined sample voice segments for each type of acceptability level determined by listener panel testing. The expert listener was trained using this software package until she could match listener panel ratings of acceptability well. The voice segments used in training were limited to those having listener panel data available. Numerous voice segments for technologies such as Digital European Cordless Telephone (DECT), Personal Handy Phone System (PHS), and Wireless Access Communication System (WACS) were available; however, it is unlikely that all types of digital noise and distortions were represented in the training material.

Figure 3.27 shows the relationship between expert listener ratings and percent acceptability (the percentage of listeners rating a given voice segment as acceptable). The boxes represent the middle half of the data (from the 25^{th} percentile to the 75^{th} percentile). The solid circles represent the median percent acceptabilities for each of the expert listener ratings. The lines extending out of the boxes depict the spread of the data. A large variance in percent acceptability is seen for each expert listener rating. A rating of unacceptable, for instance, includes voice segments that were described as acceptable by 90% of the listeners. A rating of marginally acceptable includes voice segments rated as high as 100% acceptable and as low as 0% acceptable. A rating of definitely acceptable includes voice segments rated as low as 50% acceptable. The boxes are elongated, which also show the large spread in data. Based on the data presented in Figure 3.27, the expert listener ratings do not appear to be accurate predictors of listener responses to the question “Would you consider this acceptable as portable service?”

The Pearson product-moment correlation coefficient between MOS and percent acceptability was 0.89. As would be expected, the relationship between these measures is highly correlated. We would then expect the relationship between MOS and expert listener rating to be similar to that between percent acceptability and expert listener rating. The Pearson product-moment correlation coefficient between MOS and expert listener rating was 0.54, indicating that a strong linear relationship between these measures does not exist.

The expert listener’s ratings were based on the distortion types 1 and 2 that were discussed in Section 3.6.2. This may help explain why the expert listener ratings were not better predictors of MOS’s.

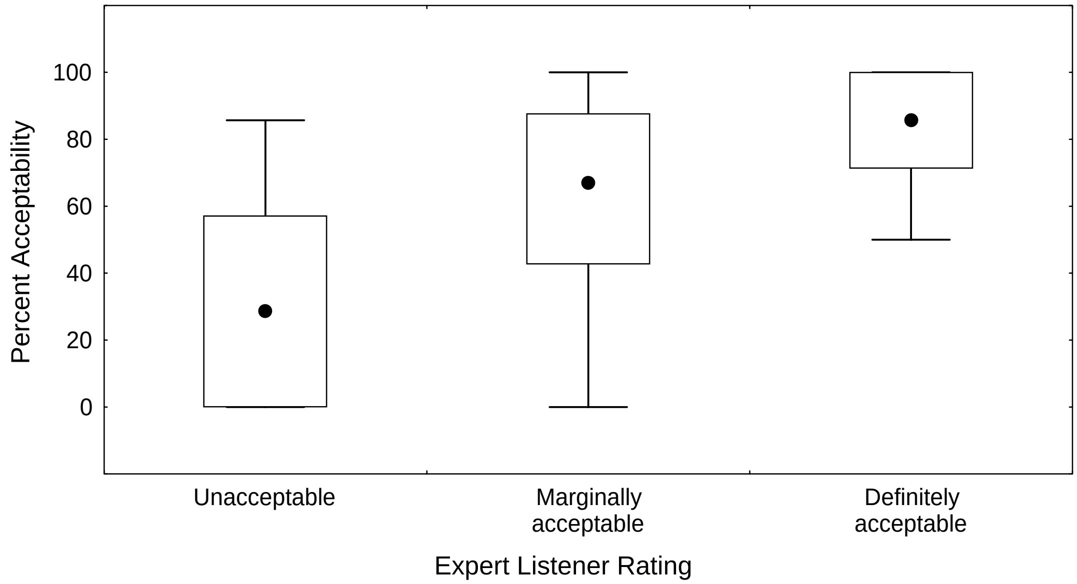


Figure 3.27. Percent acceptability vs. expert listener rating (TAG 5).

It is possible that the combination of expert listener rating, Rxlev, and Rxqual can predict MOS's. A multiple regression analysis was completed in order to determine if MOS is related to a combination of expert listener rating, Rxlev, and Rxqual. The analysis did not consider interactions among factors. The result showed that only 36.8% of the variance can be explained by expert listener rating, Rxlev, and Rxqual together and that these measures reliably account for the 36.8% of variance. From this analysis it appears that, at least at first glance, the combination of expert listener rating, Rxlev, and Rxqual does not offer any substantial predictive power over MOS's.

Expert listener ratings, average Rxlev, and average Rxqual have not offered much insight into the behavior of MOS's during this trial. One must wonder: how valid are the MOS's? Are MOS's really providing an accurate view of listener satisfaction to these voice segments?

3.6.4 Voice Quality Handoff Measurements

Voice quality handoff measurements were not made for the PCS 1900 (TAG 5) technology field trials.

3.7 Manufacturers' Statements

Statements provided by the manufacturers involved in the testing are included in this section. These statements are identical to those given in [1], except for some minor editorial changes.

3.7.1 Motorola, Inc.

Motorola extends its thanks to all participants in this very successful field test. Special thanks are extended to U S West for providing the Boulder Industry Test Bed (BITB) and their very capable technical staff. Additional thanks go to ITS and Northern Telecom for their contributions, as well as all other TAG 5 members who assisted with funding of the testing.

Motorola is pleased to have been part of the TAG 5 field test. As the first technology to complete field testing as required by the JTC, PCS 1900, based on the Groupe Speciale Mobile (GSM) technology, has laid much of the groundwork for other technologies to follow. At the same time, the efficiency and comprehensiveness of the tests have set a high standard by which others will be compared.

Motorola wishes to caution the reader from drawing conclusions about certain aspects of system performance described in this report. The emphasis of the testing was on air-interface aspects of PCS 1900. Fundamental aspects of radio system performance such as coverage, interference immunity, and voice quality were the focus of the test plan. This focused scope, combined with a limited time frame, did not permit any system parameter optimization to take place. As a consequence, inter-BSC functionality (such as handoff) did not perform with the efficiency and reliability that has become the norm in mature GSM systems worldwide.

Other advanced features available with PCS 1900, such as slow frequency hopping (SFH), and advanced frequency re-use schemes, were also outside the scope of the JTC test plan. These and other features are deserving of consideration when assessing the performance of the PCS 1900 air interface.

Certainly, one of the most significant results of this field test was an intrinsic test of inter-operability between multiple manufacturers. Only one month was required to assemble a system comprised of a switch and base stations from multiple vendors, providing seamless handoffs to mobile units from multiple vendors. The success of this venture is a testimony to the open architecture of PCS 1900.

The results of this field test will hopefully serve as a valuable source of information to the PCS industry. Motorola is happy to have been a part of this cooperative effort.

3.7.2 Northern Telecom, Inc.

Northern Telecom would like to acknowledge all the participants for their contributions towards the success of this PCS 1900 technology field trial, the first technology to be tested as required by the JTC. This includes the contributions from all TAG 5 members, Motorola, the staff and facilities of U S West for the use of the BITB, and ITS.

The robustness and maturity of the GSM-based technology is evidenced by two separate manufacturers, in a very short time frame, building a seamless operational network within a metropolitan area. PCS 1900 was the first technology to be tested, and as such encountered some nontechnology dependent testing difficulties. Future tests with other technologies will draw on this experience base with enhanced testing procedures providing more exacting outcomes.

With the time constraints, it was not possible to perform a thorough evaluation on many of the PCS 1900/GSM technology features (e.g., short message, quality control with DTX, frequency hopping, power stepping, and handoff deltas). Handoffs performed correctly for the environment they were set for, but to ensure inter-BSC handoffs in extremely weak areas where no overlap was predicted to occur, deltas and margins were set to values which are not representative of an optimized system.

One would expect that MOS scoring should have a direct correlation with Rxlev and/or Rxqual. Additional analysis must be performed to identify the cause of the low correlation, while recognizing that the system was not optimized for voice quality (e.g., no echo cancellers were deployed towards the public switched telephone network (PSTN) although the BTS/ BSC distance was over 700 mi).

Northern Telecom is pleased to have assisted in the demonstration of PCS 1900, towards the goal of rapid introduction of the technology into the industry. Furthermore, Northern Telecom trusts that these results will be found useful by others in the PCS industry.